EP 1.2: G51/[illegible]/v.2
036

POLICY OPTIONS FOR STABILIZING GLOBAL CLIMATE

DRAFT

REPORT TO CONGRESS

Volume II: Chapters VI-IX

United States Environmental Protection Agency
Office of Policy, Planning and Evaluation

February 1989

READEX FICHE best copy available

POLICY OPTIONS FOR STABILIZING GLOBAL CLIMATE

DRAFT

REPORT TO CONGRESS

Volume II: Chapters VII-IX

Editors: Daniel A. Lashof and Dennis A. Tirpak

United States Environmental Protection Agency
Office of Policy, Planning, and Evaluation

February 1989

DISCLAIMER

This draft is being circulated for review and comment and does not necessarily reflect the official position of the U.S. Environmental Protection Agency. Mention of trade names does not constitute an endorsement.

SUMMARY TABLE OF CONTENTS

EXECUTIVE SUMMARY (Bound under separate cover)

VOLUME I

CHAPTER I: INTRODUCTION I-1
CHAPTER II: GREENHOUSE GAS TRENDS II-1
CHAPTER III: CLIMATIC CHANGE III-1
CHAPTER IV: HUMAN ACTIVITIES AFFECTING TRACE GASES AND CLIMATE IV-1
CHAPTER V: THINKING ABOUT THE FUTURE V-1
CHAPTER VI: SENSITIVITY ANALYSES VI-1

VOLUME II

CHAPTER VII: TECHNICAL OPTIONS FOR REDUCING GREENHOUSE GAS EMISSIONS . VII-1
CHAPTER VIII: POLICY OPTIONS VIII-1
CHAPTER IX: INTERNATIONAL COOPERATION TO REDUCE GREENHOUSE GAS EMISSIONS IX-1

DETAILED TABLE OF CONTENTS

EXECUTIVE SUMMARY
(Bound under separate cover)

INTRODUCTION 1
  Congressional Request for Reports 1
  Previous Studies 2
  Goals of this Study 4
  Approach Used to Prepare this Report 6
  Limitations 9

HUMAN IMPACT ON THE CLIMATE SYSTEM 11
  The Greenhouse Gas Buildup 11
  The Impact of Greenhouse Gases on Global Climate 17

SCENARIOS FOR POLICY ANALYSIS 19
  Defining Scenarios 19
  Scenarios with Unimpeded Emissions Growth 22
  The Impact of Policy Choices 29
  Sensitivity of Results to Alternative Assumptions 45

EMISSIONS REDUCTION STRATEGIES BY ACTIVITY 54
  Energy Production and Use 56
  Industrial Activity 66
  Changes in Land Use 71
  Agricultural Practices 75

THE NEED FOR POLICY RESPONSES 77
  A Wide Range of Policy Choices 78
  The Timing of Policy Responses 79

FINDINGS 83

  I. Uncertainties regarding climatic change are large, but there is a growing consensus in the scientific community that significant global warming due to anthropogenic greenhouse gas emissions is probable over the next century, and that rapid climatic change is possible. 83

  II. Measures undertaken to limit greenhouse gas emissions would decrease the magnitude and speed of global warming, regardless of uncertainties about the response of the climate system. 85

  III. No single country or source will contribute more than a fraction of the greenhouse gases that will warm the world; any overall solution will require cooperation of many countries and reductions in many sources. 87

  IV. A wide range of policy choices is available to reduce greenhouse gas emissions while promoting economic development, environmental, and social goals. 89

DETAILED TABLE OF CONTENTS (Continued)

VOLUME I

CHAPTER I

INTRODUCTION

INTRODUCTION I-2
    The Earth's Climate and Global Change I-2

CONGRESSIONAL REQUEST FOR REPORTS I-3
    Goals of this Study I-4
    Report Format I-5

THE GREENHOUSE GASES I-8
    Carbon dioxide I-9
    Methane I-9
    Nitrous oxide I-12
    Chlorofluorocarbons I-12
    Other gases influencing composition I-13

PREVIOUS STUDIES I-13
    Estimates of the Climatic Effects of Greenhouse Gas Buildup I-14
    Studies of Future CO_2 Emissions I-15
    Studies of the Combined Effects of Greenhouse Gas Buildup I-20
    Major Uncertainties I-22
    Conclusions From Previous Studies I-23

CURRENT NATIONAL AND INTERNATIONAL ACTIVITIES I-26
    National Research and Policy Activities I-26
    International Activities I-27

REFERENCES I-29

CHAPTER II

GREENHOUSE GAS TRENDS

FINDINGS II-2

INTRODUCTION II-5

CARBON DIOXIDE II-7
    Concentration History and Geographic Distribution II-7
        Mauna Loa II-8
        Ice-core Data II-9
        GMCC Network II-10

DETAILED TABLE OF CONTENTS (Continued)

  Sources and Sinks II-14
    Fossil Carbon Dioxide II-14
    Biospheric Cycle II-16
    Ocean Uptake II-17
  Chemical and Radiative Properties/Interactions II-18

METHANE II-22
  Concentration History and Geographic Distribution II-22
  Sources and Sinks II-24
  Chemical and Radiative Properties/Interactions II-29

NITROUS OXIDE II-30
  Concentration History and Geographic Distribution II-30
  Sources and Sinks II-32
  Chemical and Radiative Properties/Interactions II-35

CHLOROFLUOROCARBONS (CFCs) II-36
  Concentration History and Geographic Distribution II-36
  Sources and Sinks II-37
  Chemical and Radiative Properties/Interactions II-39

OZONE II-40
  Concentration History and Geographic Distribution II-40
  Sources and Sinks II-43
  Chemical and Radiative Properties/Interactions II-44

OTHER FACTORS AFFECTING COMPOSITION II-45
  Global Tropospheric Chemistry II-46
    Carbon Monoxide II-47
    Nitrogen Oxides II-48
  Stratospheric Ozone and Circulation II-49

CONCLUSION II-50

REFERENCES II-59

CHAPTER III

CLIMATIC CHANGE

FINDINGS III-2

INTRODUCTION III-4

CLIMATIC CHANGE IN CONTEXT III-6

CLIMATE FORCINGS III-8
  Solar Luminosity III-12
  Orbital Parameters III-13
  Volcanoes III-13
  Surface Properties III-14
  The Role of Greenhouse Gases III-14

DETAILED TABLE OF CONTENTS (Continued)

Internal Variations III-15

PHYSICAL CLIMATE FEEDBACKS III-15
  Water Vapor - Greenhouse III-17
  Snow and Ice III-17
  Clouds III-19

BIOGEOCHEMICAL CLIMATE FEEDBACKS III-20
  Release of Methane Hydrates III-20
  Oceanic Change III-22
    Ocean Chemistry III-23
    Ocean Mixing III-23
    Ocean Biology and Circulation III-24
  Changes in Terrestrial Biota III-25
    Vegetation Albedo III-25
    Carbon Storage III-26
    Other Terrestrial Biotic Emissions III-26
    Summary III-27

EQUILIBRIUM CLIMATE SENSITIVITY III-28

THE RATE OF CLIMATIC CHANGE III-31

CONCLUSION III-35

REFERENCES III-37

CHAPTER IV

HUMAN ACTIVITIES AFFECTING TRACE GASES AND CLIMATE

FINDINGS IV-2

INTRODUCTION IV-5

HISTORICAL OVERVIEW OF POPULATION TRENDS IV-5
  Global Population Trends IV-7
  Population Trends by Region IV-7
    Industrialized Countries IV-10
    Developing Countries IV-10

ENERGY CONSUMPTION IV-12
  History of Fossil-Fuel Use IV-13
  Current Energy Use Patterns and Greenhouse Gas Emissions IV-18
    Emissions by Sector IV-20
    Fuel Production and Conversion IV-25
  Future Trends IV-27
    The Fossil-Fuel Supply IV-29
    Future Energy Demand IV-29

DETAILED TABLE OF CONTENTS (Continued)

UNCERTAINTIES IN THE GLOBAL CARBON CYCLE VI-41
- Unknown Sink In Carbon Cycle VI-43
- Amount of CO_2 From Deforestation VI-44
- Alternative CO_2 Models of Ocean Chemistry and Circulation VI-47

ASSUMPTIONS ABOUT CLIMATE SENSITIVITY AND TIMING VI-50
- Sensitivity of the Climate System VI-50
- Rate of Heat Diffusion VI-53

ASSUMPTIONS ABOUT ATMOSPHERIC CHEMISTRY: A COMPARISON OF MODELS . . . VI-54
- Model Descriptions VI-56
  - Assessment Model for Atmospheric Composition VI-56
  - Isaksen Model VI-57
  - Thompson et al. Model VI-58
- Results from the Common Scenarios VI-59

EVALUATION OF UNCERTAINTIES USING AMAC VI-67
- Atmospheric Lifetime of CFC-11 . . . . VI-67
- Interaction of Chlorine with Column Ozone VI-69
  - Sensitivity of Tropospheric Ozone to CH_4 Abundance VI-69
  - Sensitivity of OH to NO_x VI-71

BIOGEOCHEMICAL FEEDBACKS VI-72
- Ocean Circulation VI-72
- Methane Feedbacks VI-73
- Combined Feedbacks VI-75

REFERENCES VI-78

VOLUME II

CHAPTER VII

TECHNICAL OPTIONS FOR REDUCING GREENHOUSE GAS EMISSIONS

PART ONE: ENERGY SERVICES VII-27

TRANSPORTATION SECTOR VII-32
- Near-Term Technical Options: Industrialized Countries VII-36
  - Light-Duty Vehicles VII-38
  - Freight Transport Vehicles VII-49
  - Aircraft VII-52
  - Control of NO_x and CO Emissions from Mobile Sources VII-53
- Near-Term Technical Options: Developing Countries VII-55
  - Fuel-Efficiency Improvements VII-57
  - Improving Existing Vehicles VII-58
  - Alleviating Congestion and Improving Roads VII-58
  - Alternative Modes of Transportation VII-59
  - Alternative Fuels VII-60
- Near-Term Technical Options: Soviet Bloc Countries VII-61

DETAILED TABLE OF CONTENTS (Continued)

Summary of Near-Term Technical Potential in the Transportation Sector VII-62
Long-Term Potential in the Transportation Sector VII-63
    Urban Planning and Mass Transit VII-63
    Alternative Fuels VII-65
    Expanded Use of Emerging Technologies VII-66
RESIDENTIAL/COMMERCIAL SECTOR VII-67
Near-Term Technical Options: Industrialized Countries VII-71
    Improvements in Space Conditioning VII-71
    Indoor Air Quality VII-80
    Lighting VII-81
    Appliances VII-83
Near-Term Technical Options: Developing Countries VII-83
    Increasing Efficiency of Fuelwood Use VII-85
    Substituting More Efficient Fuels VII-87
    Retrofit Efficiency Measures for the Modern Sector VII-88
    New Homes and Commercial Buildings VII-89
Near-Term Technical Options: Soviet Bloc Countries VII-90
Summary of Near-Term Technical Potential in the Residential/Commercial Sector VII-91
Long-Term Potential in the Residential/Commercial Sector VII-92
INDUSTRIAL SECTOR VII-93
Near-Term Technical Options: Industrialized Countries VII-98
    Accelerated Efficiency Improvements in Energy-Intensive Industries VII-98
    Aggressive Efficiency Improvements of Other Industries VII-100
    Cogeneration VII-101
Near-Term Technical Options: Developing Countries VII-102
    Technological Leapfrogging VII-103
    Alternative Fuels VII-104
    Retrofit Energy Efficiency Programs VII-105
    Agricultural Energy Use VII-106
Near-Term Technical Options: Soviet Bloc Countries VII-107
Summary of Near-Term Technical Potential in the Industrial Sector VII-111
Long-Term Potential in the Industrial Sector VII-112
    Structural Shifts VII-112
    Advanced Process Technologies VII-113
    Non-fossil Energy VII-115

PART TWO: ENERGY SUPPLY VII-116

FOSSIL FUELS VII-117
Refurbishment of Existing Powerplants VII-121
Clean Coal Technologies and Repowering VII-122
Cogeneration VII-123
Natural Gas Substitution VII-124
    Natural Gas Use At Existing Powerplants VII-124
    Advanced Gas-Fired Combustion Technologies VII-125
    Natural Gas Resource Limitations VII-127
    Additional Gas Resources VII-130
Emission Controls VII-132
    NO_x Controls VII-132
    CO_2 Controls VII-133

DETAILED TABLE OF CONTENTS (Continued)

INDUSTRIAL PROCESSES IV-31
- Chlorofluorocarbons, Halons, and Chlorocarbons IV-33
  - Historical Development and Uses IV-33
  - The Montreal Protocol IV-37
- Landfill Waste Disposal IV-40
- Cement Manufacture IV-43

LAND USE CHANGE IV-45
- Deforestation IV-47
- Biomass Burning IV-50
- Wetland Loss IV-51

AGRICULTURAL ACTIVITIES IV-55
- Enteric Fermentation In Domestic Animals IV-55
- Rice Cultivation IV-56
- Use of Nitrogenous Fertilizer IV-61

IMPACT OF CLIMATIC CHANGE ON ANTHROPOGENIC EMISSIONS IV-63

REFERENCES IV-67

CHAPTER V

THINKING ABOUT THE FUTURE

FINDINGS V-2

INTRODUCTION V-4

APPROACH TO ANALYZING FUTURE EMISSIONS V-5
- Production V-7
- Consumption V-11

SCENARIOS FOR POLICY ANALYSIS V-13
- Scenarios with Unimpeded Emissions Growth V-17
- Scenarios with Stabilizing Policies V-21

ANALYTICAL FRAMEWORK V-22
- Energy Module V-25
- Industry Module V-26
- Agriculture Module V-26
- Land Use and Natural Source Module V-27
- Ocean Module V-27
- Atmospheric Composition and Temperature Module V-28
- Assumptions V-29
  - Population Growth Rates V-29
  - Economic Growth Rates V-29
  - Oil Prices V-30
- Limitations V-30

DETAILED TABLE OF CONTENTS (Continued)

SCENARIO RESULTS V-33
  Energy Sector V-33
    End-use Consumption V-33
    Primary Energy Supply V-39
    Greenhouse Gas Emissions From Energy Production and Use V-44
    Comparison to Previous Studies V-45
  Industrial Processes V-56
    Halocarbon Emissions V-56
    Emissions From Landfills and Cement V-59
  Changes in Land Use V-60
  Agricultural Activities V-63
  Total Emissions V-64
  Atmospheric Concentrations V-71
  Global Temperature Increases V-76
  Comparison with General Circulation Model Results V-81
  Relative Effectiveness of Selected Strategies V-82

CONCLUSIONS V-82

REFERENCES V-87

CHAPTER VI

SENSITIVITY ANALYSES

FINDINGS VI-3

INTRODUCTION VI-12

ASSUMPTIONS ABOUT THE MAGNITUDE AND TIMING OF GLOBAL CLIMATE STABILIZATION STRATEGIES VI-12
  No Participation by the Developing Countries VI-13
  Delay in Adoption of Policies VI-17

ASSUMPTIONS AFFECTING RATES OF TECHNOLOGICAL CHANGE VI-18
  Availability of Non-Fossil Technologies VI-18
  Cost and Availability of Fossil Fuels VI-22
    High Coal Prices VI-22
    Alternative Oil and Natural Gas Supply Assumptions VI-24
  Availability of Methanol-Fueled Vehicles VI-29

ATMOSPHERIC COMPOSITION: COMPARISON OF MODEL RESULTS TO ESTIMATES OF HISTORICAL CONCENTRATIONS VI-30

ASSUMPTIONS ABOUT TRACE-GAS SOURCES AND STRENGTHS VI-34
  Methane Sources VI-35
  Nitrous Oxide Emissions From Fertilizer VI-38
    Anhydrous Ammonia VI-38
    N_2O Leaching From Fertilizer VI-39
  N_2O Emissions From Combustion VI-39

DETAILED TABLE OF CONTENTS (Continued)

Emerging Electricity Generation Technologies VII-134
Fuel cells VII-134
Magnetohydrodynamics (MHD) VII-136

BIOMASS VII-137
Direct Firing of Biomass VII-138
Charcoal Production VII-140
Anaerobic Digestion VII-141
Gasification VII-142
Liquid Fuels From Biomass VII-143
Methanol VII-143
Ethanol VII-145
Other VII-146

SOLAR ENERGY VII-146
Solar Thermal VII-147
Parabolic Troughs VII-147
Parabolic Dishes VII-149
Central Receivers VII-149
Solar Ponds VII-150
Solar photovoltaic VII-150
Crystalline Cells VII-152
Thin-Film Technologies VII-153
Multi-Junction Technologies VII-154

ADDITIONAL PRIMARY RENEWABLE ENERGY OPTIONS VII-155
Hydroelectric Power VII-155
Industrialized Countries VII-155
Developing Countries VII-157
Wind Energy VII-158
Geothermal energy VII-159
Ocean Energy VII-162

NUCLEAR POWER VII-165
Nuclear Fission VII-165
Nuclear Fusion VII-170

ELECTRICAL SYSTEM OPERATION IMPROVEMENTS VII-171
Transmission and Distribution VII-171
Superconductors VII-172
Storage Technologies VII-173
Types of Storage Technologies VII-174

HYDROGEN VII-176

PART THREE: INDUSTRY VII-178

CFCs AND RELATED COMPOUNDS VII-178
Technical Options For Reducing Emissions VII-182
Chemical Substitutes VII-182
Engineering Controls VII-184
Product Substitutes VII-185

DETAILED TABLE OF CONTENTS (Continued)

Summary of Technical Potential VII-187

METHANE EMISSIONS FROM LANDFILLS VII-187
  Methane Recovery VII-190
  Recycling and Resource Recovery VII-192
  CO_2 Emissions From Cement Production VII-193

PART FOUR: FORESTRY VII-195

FORESTS AND CARBON EMISSIONS VII-195

DEFORESTATION VII-197

TECHNICAL CONTROL OPTIONS VII-202
  Reduce Demand for Forest Land and Products VII-206
    Option 1: Slow Deforestation by Introducing Sustainable Forest Use Systems . . . VII-209
    Option 2: Substitute Sustainable Agriculture for Swidden Forest Practices VII-210
    Option 3: Reduce Demand For Other Land Uses That Have Deforestation As A Byproduct VII-217
    Option 4: Increase Conversion Efficiencies Of Technologies Using Fuelwood . . . VII-218
    Option 5: Decrease Production of Disposable Forest Products VII-218
    Substitute durable wood or non-wood products for high-volume disposable uses of wood VII-219
    Expand recycling programs for forest products VII-220
  Increase Supply of Forested Land and Forest Products VII-220
    Option 1: Increase Forest Productivity: Manage Temperate Forests For Higher Yields VII-220
    Option 2: Increase Forest Productivity: Improve Natural Forest Management of Tropical Little-Disturbed And Secondary Forests VII-222
    Option 3: Increase Forest Productivity: Plantation Forests VII-224
    Option 4: Improve Forest Harvesting Efficiency VII-228
    Option 5: Expand Current Tree Planting Programs in the Temperate Zone VII-229
    Option 6: Reforest Surplus Agricultural Lands VII-231
    Option 7: Reforest Urban Areas VII-234
    Option 8: Afforestation for Highway Corridors VII-235
    Option 9: Reforest Tropical Countries VII-236
    Obstacles to Large-Scale Reforestation in Industrialized Countries VII-241
    Obstacles to Reforestation in Developing Countries VII-243
  Summary of Forestry Technical Control Options VII-244

PART FIVE: AGRICULTURE VII-249

RICE CULTIVATION VII-252
  Existing Technologies and Management Practices VII-253
  Emerging Technologies VII-257
  Research Needs and Economic Considerations VII-258

USE OF NITROGENOUS FERTILIZER VII-259
  Existing Technologies and Management Practices VII-260
    Management Practices That Affect N_2O Production VII-260
    Technologies that Improve Fertilization Efficiency VII-262

DETAILED TABLE OF CONTENTS (Continued)

Emerging Technologies VII-263
Research Needs and Economic Considerations VII-264

ENTERIC FERMENTATION IN DOMESTIC ANIMALS VII-265
Methane Emissions from Livestock VII-268
Existing Technologies and Management Practices VII-269
Emerging Technologies VII-272
Research Needs and Economic Considerations VII-273

CHAPTER VIII

POLICY OPTIONS

FINDINGS VIII-2

INTRODUCTION VIII-6

INTERNALIZING THE COST OF CLIMATE CHANGE RISKS VIII-8
Evidence of Market Response to Economic Incentives: Energy Pricing VIII-9
Financial Mechanisms to Promote Energy Efficiency VIII-14
Creating Markets for Conservation VIII-16
Limits to Price-Oriented Policies VIII-18

REGULATIONS AND STANDARDS VIII-22
Existing Regulations that Restrict Greenhouse Gas Emissions VIII-23
Regulation of Chlorofluorocarbons VIII-24
Energy Efficiency Standards VIII-25
Air Pollution Regulations VIII-28
Waste Management VIII-29
Utility Regulation VIII-31
Existing Regulations that Encourage Emissions Reductions VIII-35

RESEARCH AND DEVELOPMENT VIII-39
Energy Research and Development VIII-40
Global Forestry Research & Development VIII-45
Research to Eliminate Emissions of CFCs VIII-46

INFORMATION AND TECHNICAL ASSISTANCE PROGRAMS VIII-47

CONSERVATION EFFORTS BY FEDERAL AGENCIES VIII-50

STATE AND LOCAL EFFORTS VIII-52

PRIVATE SECTOR EFFORTS VIII-57

COMPLEMENTARY STRATEGIES TO REDUCE GREENHOUSE GAS EMISSIONS VIII-59

IMPLICATIONS OF POLICY CHOICES AND TIMING VIII-63

DETAILED TABLE OF CONTENTS (Continued)

SENSITIVITY TESTS OF THE EFFECT OF ALTERNATIVE POLICIES ON GREENHOUSE GAS EMISSIONS: RISK TRADE-OFFS VIII-67
Policies That Increase Greenhouse Gas Emissions VIII-69
Policies Designed to Reduce Greenhouse Gas Emissions VIII-76
Conclusions From the Sensitivity Tests VIII-78

REFERENCES VIII-83

CHAPTER IX

INTERNATIONAL COOPERATION TO REDUCE GREENHOUSE GAS EMISSIONS

FINDINGS IX-2

INTRODUCTION IX-4

THE CONTEXT FOR POLICIES INFLUENCING GREENHOUSE GAS EMISSIONS IN DEVELOPING COUNTRIES IX-5
Economic Development and Energy Use IX-7
Oil Imports, Capital Shortages, and Energy Efficiency IX-13
Greenhouse Gas Emissions and Technology Transfer IX-17

STRATEGIES FOR REDUCING GREENHOUSE GAS EMISSIONS IX-18
International Lending and Bilateral Aid IX-20
U.S. Bilateral Assistance Programs IX-21
Policies and Programs of Multilateral Development Banks IX-24
New Directions IX-31

REDUCING GREENHOUSE GAS EMISSIONS IN EASTERN BLOC NATIONS IX-33

U.S. LEADERSHIP TO PROMOTE INTERNATIONAL COOPERATION IX-36
Restricting CFCs to Protect the Ozone Layer IX-36
International Efforts to Halt Tropical Deforestation IX-38
Ongoing Efforts Toward International Cooperation IX-42

REFERENCES IX-45

LIST OF FIGURES

Page

Executive Summary (bound under separate cover)

1 Carbon Dioxide Concentrations at Mauna Loa and Fossil Fuel CO_2 Emissions . . 3
2 Structure of the Atmospheric Stabilization Framework 8
3 Greenhouse Gas Contributions to Global Warming 12
4 Impact of CO_2 Emissions Reductions on Atmospheric Concentrations 14
5 Atmospheric Concentrations 25
6 Realized Warming: No Response Scenarios 27
7 Realized Warming: No Response and Stabilizing Policy Scenarios 31
8 Stabilizing Policy Strategies: Decrease in Equilibrium Warming Commitment 34
9 Rapid Reduction Strategies: Additional Decrease in Equilibrium Warming Commitment 37
10 Share of Greenhouse Gas Emissions by Region 41
11 Increase in Realized Warming When Developing Countries Do Not Participate 43
12 Increase in Realized Warming Due to Global Delay in Policy Adoption 44
13 Accelerated Emissions Cases: Percent Increase in Equilibrium Warming Commitment 46
14 Impact of Climate Sensitivity on Realized Warming 48
15 Activities Contributing to Global Warming 55
16 Primary Energy Supply by Type 58
17 CO_2 Emissions From Deforestation 73

VOLUME I

Chapter I

1-1 Carbon Dioxide Concentrations at Mauna Loa and Fossil Fuel CO_2 Emissions I-10
1-2 Impact of CO_2 Emissions Reductions on Atmospheric Concentrations I-11

Chapter II

2-1 Greenhouse Gas Contributions to Global Warming II-6
2-2 Carbon Dioxide Concentration II-11
2-3 CO_2 Atmospheric Concentrations by Latitude II-12
2-4 The Carbon Cycle II-15
2-5 Gas Absorption Bands II-20
2-6 Methane Concentration II-23
2-7 Current Emissions of Methane by Source II-25
2-8 Nitrous Oxide Concentrations II-31
2-9 Temperature Profile and Ozone Distribution in the Atmosphere II-41

LIST OF FIGURES (Continued)

Page

Chapter III

3-1 Surface Air Temperature III-7
3-2 Oxygen Isotope Record From Greenland Ice Cores III-9
3-3 Carbon Dioxide and Temperatures Records From Antarctic Ice Core III-10
3-4 Oxygen Isotope Record From Deep Sea Sediment-Cores III-11
3-5 Global Energy Balance III-16
3-6 Equilibrium Temperature Changes from Doubled CO_2 . . . . III-18
3-7 Greenhouse Gas Feedback Processes III-21

Chapter IV

4-1 Regional Contribution to Greenhouse Warming -- 1980s IV-6
4-2 Regional Population Growth -- 1750-1985 . . . . IV-8
4-3 Global Energy Demand by Type -- 1950-1985 . . . . IV-14
4-4 CO_2 Emissions Due to Fossil Fuel Consumption -- 1860-1985 . . . . IV-16
4-5 Global Commercial Energy Demand by Region IV-17
4-6 1985 Sectoral Energy Demand by Region IV-19
4-7 Potential Future Energy Demand IV-32
4-8 Historical Production of CFC-11 and CFC-12 . . . . IV-36
4-9 CFC-11 and CFC-12 Production/Use for Various Countries IV-39
4-10 CO_2 Emissions from Cement Production -- 1950-1985 . . . . IV-44
4-11 Cement Production in Selected Countries -- 1951-1985 . . . . IV-46
4-12 Net Release of Carbon from Tropical Deforestation -- 1980 . . . . IV-48
4-13 Wetland Area and Associated Methane Emissions IV-53
4-14 Trends in Domestic Animal Populations -- 1890-1985 . . . . IV-57
4-15 Rough Rice Production -- 1984 . . . . IV-59
4-16 Rice Area Harvested -- 1984 . . . . IV-60
4-17 Nitrogen Fertilizer Consumption -- 1984/1985 . . . . IV-64

Chapter V

5-1 Total U.S. Energy Consumption per GNP Dollar -- 1900-1985 . . . . V-8
5-2 Consumption of Basic Materials V-10
5-3 Population by Region V-19
5-4 Structure of the Atmospheric Stabilization Framework V-23
5-5 Geopolitical Regions For Climate Analyses V-24
5-6 End-Use Fuel Demand by Region V-34
5-7 End-Use Electricity Demand by Region V-35
5-8 Share of End-Use Energy Demand by Sector V-38
5-9 Primary Energy Supply by Type V-40
5-10 Share of Primary Energy Supply by Type V-41
5-11 Energy Demand for Synthetic Fuel Production V-42
5-12 Emissions of Major CFCs V-58
5-13 CO_2 Emissions from Deforestation V-62
5-14 CO_2 Emissions by Type V-66
5-15 Share of CO_2 Emissions by Region V-68
5-16 CH_4 Emissions by Type V-69

LIST OF FIGURES (Continued)

Page

5-17 Share of CH_4 Emissions by Region V-70
5-18 Atmospheric Concentrations V-72
5-19 Realized and Equilibrium Warming V-77
5-20 Relative Contribution to Warming by 2100 . . . . V-80
5-21 Stabilizing Policy Strategies: Decrease in Equilibrium Warming Commitment . . . V-83

Chapter VI

6-1 Increase in Realized Warming When Developing Countries Do Not Participate VI-16
6-2 Increase in Realized Warming Due to Global Delay in Policy Adoption VI-19
6-3 Availability of Non-Fossil Energy Options VI-21
6-4 Impact of 1% Per Year Real Escalation in Coal Prices VI-23
6-5 Impact of Higher Oil Resources On Total Primary Energy Supply VI-26
6-6 Impact of Higher Natural Gas Resources on Total Primary Energy Supply VI-28
6-7 Realized Warming Through 1985 . . . . VI-32
6-8 Increase in Realized Warming Due to Changes in the Methane Budget VI-37
6-9 Change in Atmospheric Concentration of N_2O Due to Leaching VI-40
6-10 Change in Atmospheric Concentration of N_2O Due to Combustion VI-42
6-11 Impact on Realized Warming Due to Size of Unknown Sink VI-45
6-12 CO_2 From Deforestation Assuming High Biomass VI-46
6-13 Impact of High Biomass Assumptions on Atmospheric Concentration of CO_2 . . . VI-48
6-14 Comparison of Different Ocean Models VI-51
6-15 Impact of Climate Sensitivity on Realized Warming VI-52
6-16 Change in Realized Warming Due to Rate of Ocean Heat Uptake VI-55
6-17 Regional Differences for Urban Areas With Different Emissions of CO and NO VI-64
6-18 OH and Ozone Perturbations in the Isaksen and Hov Model VI-66
6-19 Sensitivity of Atmospheric Concentration of CFC-11 to Its Lifetime VI-68
6-20 Change in Realized Warming Due to Rate of Interaction of CLx With Ozone VI-70
6-21 Increase in Realized Warming Due to Change in Ocean Circulation VI-74
6-22 Increase in Realized Warming Due to Methane Feedbacks VI-76
6-23 Increase in Realized Warming Due to Change in Combined Feedbacks VI-77

LIST OF FIGURES (Continued)

Page

VOLUME II

Chapter VII

7-1 Current Contribution to Global Warming VII-20
7-2 Global Energy Use by End-Use VII-28
7-3 Secondary Energy Consumption by Region VII-30
7-4 End-Use Energy Demand by Sector VII-33
7-5 Transportation Energy Use by Region VII-35
7-6 Components of Transportation Energy Use in the OECD: 1985 . . . . VII-37
7-7 U.S. Residential/Commercial Energy Use VII-68
7-8 Residential/Commercial Energy Use by Region VII-70
7-9 Industrial Energy Use by Region VII-97
7-10 Electricity Utility Demand by Fuel Type VII-118
7-11 Average Fossil Powerplant Efficiency VII-120
7-12 Strategies for Improving Efficiency of Biomass Use VII-139
7-13 Basic Solar Thermal Technologies VII-148
7-14 Photovoltaic Electricity Costs VII-151
7-15 Nuclear Capital Costs VII-167
7-16 Industrial Process Contribution to Global Warming VII-179
7-17 Emissions of Major CFC's VII-180
7-18 CH_4 Emissions by Type VII-188
7-19 Movement of Tropical Forest Lands Among Stages of Deforestation and Potential Technical Response Options VII-198
7-20 Population Growth, Road Building, and Deforestation in Amazonia VII-201
7-21 Model Agroforestry Farm Layout, Rwanda VII-214
7-22 Agricultural Practices Contribution to Global Warming VII-250
7-23 Trace Gas Emissions From Agricultural Activities VII-251

Chapter VIII

8-1 Energy Intensity Reductions, 1973-1983 . . . . VIII-11
8-2 U.S. Electricity Demand and Price VIII-15
8-3 Cost of Driving Versus Automotive Fuel Economy VIII-21
8-4 U.S. Carbon Monoxide Emissions VIII-30
8-5 Changes in U.S. Renewable Energy R&D Priorities Over Time VIII-42
8-6 Cost of Potential Residential Electricity Conservation in Michigan by 2000 . . . . VIII-55
8-7 U.S. Energy Consumption By Fuel Share VIII-66
8-8 Atmospheric Response to Emissions Cutoff VIII-68
8-9 Actual and Projected U.S. Coal Production VIII-70
8-10 Accelerated Emissions Cases: Percent Increase in Equilibrium Warming Commitment VIII-74
8-11 Rapid Reduction Strategies: Additional Decrease in Equilibrium Warming Commitment VIII-79

LIST OF FIGURES (Continued)

Page

Chapter IX

9-1 Greenhouse Gas Emissions By Region IX-6

LIST OF TABLES

Page

Executive Summary (bound under separate cover)

1 Approximate Reductions in Anthropogenic Emissions Required to Stabilize Atmospheric Concentrations at Current Levels 15
2 Overview of Scenario Assumptions 21
3 Current and Projected Trace Gas Emissions Estimates 24
4 Scenario Results for Realized and Equilibrium Warming 33
5 Examples of Policy Responses by the Year 2000 39
6 Sensitivity Analysis: Impact on Realized Warming and Equilibrium Warming . . . 50
7 Key Global Indicators for Energy and CO_2 61
8 Major Chlorofluorocarbons, Halons, and Chlorocarbons: Statistics and Uses 68

VOLUME I

Chapter II

2-1 Radiative Forcing for a Uniform Increase in Trace Gases From Current Levels . . II-21
2-2 Trace Gas Data II-51

Chapter IV

4-1 Regional Demographic Indicators IV-9
4-2 Emission Rate Differences by Sector IV-21
4-3 End-Use Energy Consumption Patterns for the Residential/Commercial Sectors IV-24
4-4 Carbon Dioxide Emission Rates for Conventional and Synthetic Fuels IV-28
4-5 Estimates of Global Fossil-Fuel Resources IV-30
4-6 Major Halocarbons: Statistics and Uses IV-34
4-7 Estimated 1985 World Use of Potential Ozone-Depleting Substances IV-38
4-8 Refuse Generation Rates in Selected Cities IV-42
4-9 Land-Use: 1850-1980 . . . . IV-49
4-10 Summary Data on Area and Biomass Burned IV-52
4-11 Nitrous Oxide Emissions by Fertilizer Type IV-62

Chapter V

5-1 Overview of Scenario Assumptions V-14
5-2 Economic Growth Assumptions V-18
5-3 Key Global Indicators V-46
5-4 Comparison of No Response Scenarios and NEPP V-48
5-5 Comparison of Stabilizing Policy Scenarios and ESW V-49
5-6 Summary of Various Primary Energy Forecasts for the Year 2050 . . . . V-51
5-7 Comparison of Energy-Related Trace-Gas Emissions Scenarios V-55
5-8 Trace Gas Emissions V-65
5-9 Comparison of Estimates of Trace-Gas Concentrations in 2030 and 2050 . . . . . . V-75

LIST OF TABLES (Continued)

Page

Chapter VI

6-1 Impact of Sensitivity Analyses on Realized Warming and Equilibrium Warming . . VI-7
6-2 Comparison of Model Results to Concentrations in 1986 . . . . VI-33
6-3 Low and High Anthropogenic Impact Budgets for Methane VI-36
6-4 Comparison of Emission Estimates for EPA #2, RCW and SCW Cases VI-60
6-5 Comparison of Results from Atmospheric Chemistry Models for the Year 2050 Compared to 1985 . . . . VI-61

VOLUME II

Chapter VII

7-1 Key Technical Options by Region and Time Horizon VII-19
7-2 High Fuel Economy Prototype Vehicles VII-39
7-3 Actual New Passenger Car Fuel Efficiency VII-40
7-4 Summary of Energy Consumption and Conservation Potential With Major Residential Equipment VII-84
7-5 Reduction of Energy Intensity In the Basic Materials Industries VII-95
7-6 Energy Intensities of Selected Economies VII-108
7-7 Innovation in Steel Proudction Technology VII-110
7-8 Total U.S. Gas Reserves and Resources VII-128
7-9 CO_2 Scrubber Costs Compared to SO_2 Scrubber Costs VII-135
7-10 Estimates of Worldwide Geothermal Electric Power Capacity Potential VII-160
7-11 Capacity of Direct Use Geothermal Plants in Operation - 1984 . . . . VII-163
7-12 Geothermal Powerplants On-Line as of 1985 . . . . VII-164
7-13 Major Forestry Sector Strategies for Stabilizing Climate Change VII-203
7-14 Potential Forestry Strategies and Technical Options to Slow Climate Change VII-207
7-15 Comparison of Land Required for Sustainable Swidden Versus Agricultural Practices VII-212
7-16 Potential Carbon Fixation and Biomass Production Benefits from Agroforestry Systems VII-216
7-17 Natural and Managed Tropical Moist Forest Yields VII-223
7-18 Productivity Increases Attributable to Intensive Plantation Management VII-227
7-19 Summary of Major Tree Planting Programs in the U.S. VII-230
7-20 Estimates of CRP Program Acreage Necessary to Offset CO_2 Production from New Fossil Fuel-Fired Electric Plants, 1987-96, by Tree Species or Forest Type . . VII-233
7-21 Estimates of Forest Acreage Required to Offset Various CO_2 Emissions Goals . . VII-239
7-22 Comparison of Selected Forest Sector Control Options: Preliminary Estimates . . VII-245
7-23 Overview of Two Social Forestry Projects Proposed to Offset CO_2 Emissions of a 180-MW Electric Plant in Connecticut VII-248
7-24 Water Regime and Modern Variety Adoption for Rice Production in Selected Asian Countries VII-256
7-25 Average Meat Yield Per Animal VII-267

Chapter VIII

8-1 Energy Intensity of Selected National Economies, 1973-85 . . . . VIII-12
8-2 Payback Periods in Years for Appliances, 1972-1980 . . . . VIII-20

LIST OF TABLES (Continued)

Page

8-3 Appliance Efficiency Improvements Required by Law VIII-26
8-4 Cogeneration Facilities VIII-34
8-5 Erodible Acreage Available to Offset CO_2 Emissions From Electricity Production VIII-37
8-6 Government Efficiency Research and Development Budgets in OECD Member Countries, 1986 .... VIII-41
8-7 Federal Energy Expenditures and Cost Avoidance, FY1985-FY1987 .... VIII-51
8-8 Scenario Results for Realized and Equilibrium Warming VIII-82

Chapter IX

9-1 1985 Population and Energy Use Data From Selected Countries IX-8
9-2 Efficiency of Energy Use in Developing Countries: 1984-1985 .... IX-10
9-3 Potential for Electricity Conservation in Brazil IX-12
9-4 Net Oil Imports and Their Relation to Export Earnings for Eight Developing Countries, 1973-1984 .... IX-14
9-5 Annual Investment in Energy Supply as a Percent of Annual Total Public Investment (Early 1980s) IX-15
9-6 World Bank Estimate of Capital Requirements for Commercial Energy in Developing Countries, 1982-1992 .... IX-16
9-7 U.S. AID Forestry Expenditures by Region IX-23
9-8 World Bank Energy Sector Loans in 1987 .... IX-26
9-9 Expenditures of Multilateral and Bilateral Aid Agencies in the Energy Area IX-27
9-10 World Bank Energy Conservation Projects: Energy Sector Management Assistance Program (ESMAP) Energy Efficiency Initiatives IX-30
9-11 Energy Use in the Soviet Union and Eastern Bloc IX-34
9-12 Countries Responsible for Largest Share of Tropical Deforestation IX-41

ACKNOWLEDGEMENTS

This report would not have been possible without the tireless efforts of the primary chapter authors:

Executive Summary	Daniel Lashof Dennis Tirpak
Chapter I. Introduction	Joel Scheraga Irving Mintzer
Chapter II. Greenhouse Gas Trends	Inez Fung Michael Prather
Chapter III. Climatic Change	Daniel Lashof Alan Robock
Chapter IV. Human Activities Affecting Trace Gases and Climate	Barbara Braatz Craig Ebert
Chapter V. Thinking About the Future	Daniel Lashof Leon Schipper
Chapter VI. Sensitivity Analyses	Craig Ebert
Chapter VII. Technical Control Options	Paul Schwengels (Energy Services) Michael Adler (Renewable Energy) Dillip Ahuja (Biomass) Kenneth Andrasko (Forestry) Lauretta Burke (Agriculture) Craig Ebert (Energy Supply) Joel Scheraga (Energy Supply) John Wells (Halocarbons)
Chapter VIII. Policy Options	Alan Miller
Chapter IX. International Cooperation to Reduce Greenhouse Gas Emissions	Alan Miller Jayant Sathaye
Appendix A. Model Descriptions	William Pepper
Appendix B. Scenario Definitions	Craig Ebert
Appendix C. Results of Sensitivity Analyses	Craig Ebert

Model integration was coordinated by William Pepper and Craig Ebert, with assistance from Rossana Florez. Models and/or analysis were prepared by Irving Mintzer; Jayant Sathaye, Andrea Ketoff, Leon Schipper, and Sharad Lele; Klaus Frohberg and Phil Vande Kamp; Richard Houghton; Berrien Moore, Chris Ringo, and William Emmanuel; Michael Prather; Ivar Isaksen, Terje Berntsen, and Sverre Solberg; and Anne Thompson.

Document integration was coordinated by Craig Ebert and Barbara Braatz. Editorial assistance was provided by Susan MacMillan. Technical, graphics, and typing assistance was provided by Courtney Dinsmore, Katey Donaldson, Donald Devost, Michael Green, Karen Zambri, Judy Koput, Donna Whitlock, Margo Brown, and Cheryl LaBrecque.

Literally hundreds of other people have contributed to this report, including the organizers and attendants at four workshops sponsored by EPA to gather information and ideas, and dozens of formal and informal reviewers. We would like to thank this legion for their interest in this project, and apologize for not doing so individually. Particularly important comments were provided by, among others, Thomas Bath, Deborah Bleviss, Gary Breitenbeck, William Chandler, Robert Friedman, Howard Geller, James Hansen, Tony Janetos, Stan Johnson, Julian Jones, Michael Kavanaugh, Andrew Lacis, Michael MacCracken, Elaine Matthews, William Nordhaus, Steven Piccot, Marc Ross, Stephen Schneider, Paul Steele, Pieter Tans, Thomas Wigley, Edward Williams, and Robert Williams.

This work was conducted within EPA's Office of Policy Analysis, directed by Richard Morgenstern, within the Office of Policy Planning and Evaluation, administered by Linda Fisher. Technical support was provided by the Office of Research and Development, administered by Eric Brethauer.

CHAPTER VII

TECHNICAL OPTIONS FOR REDUCING GREENHOUSE GAS EMISSIONS

FINDINGS VII-6

INTRODUCTION VII-15
- The Relationship Between Technical Control Options and EPA's Modeling Results VII-15
- The Economics of Control Options VII-16
- The Role of Long- and Short-Term Options VII-17
- Control Techniques and Worldwide Emissions VII-18
- Organization of this Chapter VII-18
- Limitations VII-23

PART ONE: ENERGY SERVICES VII-27

TRANSPORTATION SECTOR VII-32
- Near-Term Technical Options: Industrialized Countries VII-36
  - Light-Duty Vehicles VII-38
  - Freight Transport Vehicles VII-49
  - Aircraft VII-52
  - Control of NO_x and CO Emissions from Mobile Sources VII-53
- Near-Term Technical Options: Developing Countries VII-55
  - Fuel-Efficiency Improvements VII-57
  - Improving Existing Vehicles VII-58
  - Alleviating Congestion and Improving Roads VII-58
  - Alternative Modes of Transportation VII-59
  - Alternative Fuels VII-60
- Near-Term Technical Options: Soviet Bloc Countries VII-61
- Summary of Near-Term Technical Potential in the Transportation Sector VII-62
- Long-Term Potential in the Transportation Sector VII-63
  - Urban Planning and Mass Transit VII-63
  - Alternative Fuels VII-65
  - Expanded Use of Emerging Technologies VII-66

RESIDENTIAL/COMMERCIAL SECTOR VII-67
- Near-Term Technical Options: Industrialized Countries VII-71
  - Improvements in Space Conditioning VII-71
  - Indoor Air Quality VII-80
  - Lighting VII-81
  - Appliances VII-83
- Near-Term Technical Options: Developing Countries VII-83
  - Increasing Efficiency of Fuelwood Use VII-85
  - Substituting More Efficient Fuels VII-87
  - Retrofit Efficiency Measures for the Modern Sector VII-88
  - New Homes and Commercial Buildings VII-89

Near-Term Technical Options: Soviet Bloc Countries VII-90
Summary of Near-Term Technical Potential in the Residential/Commercial Sector . VII-91
Long-Term Potential in the Residential/Commercial Sector VII-92

INDUSTRIAL SECTOR VII-93
Near-Term Technical Options: Industrialized Countries VII-98
Accelerated Efficiency Improvements in Energy-Intensive Industries VII-98
Aggressive Efficiency Improvements of Other Industries VII-100
Cogeneration VII-101
Near-Term Technical Options: Developing Countries VII-102
Technological Leapfrogging VII-103
Alternative Fuels VII-104
Retrofit Energy Efficiency Programs VII-105
Agricultural Energy Use VII-106
Near-Term Technical Options: Soviet Bloc Countries VII-107
Summary of Near-Term Technical Potential in the Industrial Sector VII-111
Long-Term Potential in the Industrial Sector VII-112
Structural Shifts VII-112
Advanced Process Technologies VII-113
Non-fossil Energy VII-115

PART TWO: ENERGY SUPPLY VII-116

FOSSIL FUELS VII-117
Refurbishment of Existing Powerplants VII-121
Clean Coal Technologies and Repowering VII-122
Cogeneration VII-123
Natural Gas Substitution VII-124
Natural Gas Use At Existing Powerplants VII-124
Advanced Gas-Fired Combustion Technologies VII-125
Natural Gas Resource Limitations VII-127
Additional Gas Resources VII-130
Emission Controls VII-132
NO_x Controls VII-132
CO_2 Controls VII-133
Emerging Electricity Generation Technologies VII-134
Fuel cells VII-134
Magnetohydrodynamics (MHD) VII-136

BIOMASS VII-137
Direct Firing of Biomass VII-138
Charcoal Production VII-140
Anaerobic Digestion VII-141
Gasification VII-142
Liquid Fuels From Biomass VII-143
Methanol VII-143
Ethanol VII-145
Other VII-146

SOLAR ENERGY VII-146
    Solar Thermal VII-147
        Parabolic Troughs VII-147
        Parabolic Dishes VII-149
        Central Receivers VII-149
        Solar Ponds VII-150
    Solar photovoltaic VII-150
        Crystalline Cells VII-152
        Thin-Film Technologies VII-153
        Multi-Junction Technologies VII-154

ADDITIONAL PRIMARY RENEWABLE ENERGY OPTIONS VII-155
    Hydroelectric Power VII-155
        Industrialized Countries VII-155
        Developing Countries VII-157
    Wind Energy VII-158
    Geothermal energy VII-159
    Ocean Energy VII-162

NUCLEAR POWER VII-165
    Nuclear Fission VII-165
    Nuclear Fusion VII-170

ELECTRICAL SYSTEM OPERATION IMPROVEMENTS VII-171
    Transmission and Distribution VII-171
        Superconductors VII-172
    Storage Technologies VII-173
        Types of Storage Technologies VII-174

HYDROGEN VII-176

PART THREE: INDUSTRY VII-178

CFCs AND RELATED COMPOUNDS VII-178
    Technical Options For Reducing Emissions VII-182
        Chemical Substitutes VII-182
        Engineering Controls VII-184
        Product Substitutes VII-185
    Summary of Technical Potential VII-187

METHANE EMISSIONS FROM LANDFILLS VII-187
    Methane Recovery VII-190
    Recycling and Resource Recovery VII-192
    CO_2 Emissions From Cement Production VII-193

PART FOUR: FORESTRY VII-195

FORESTS AND CARBON EMISSIONS VII-195

DEFORESTATION VII-197

TECHNICAL CONTROL OPTIONS VII-202
  Reduce Demand for Forest Land and Products VII-206
    Option 1: Slow Deforestation by Introducing Sustainable Forest Use Systems VII-209
    Option 2: Substitute Sustainable Agriculture for Swidden Forest Practices . . VII-210
    Option 3: Reduce Demand For Other Land Uses That Have Deforestation As A Byproduct VII-217
    Option 4: Increase Conversion Efficiencies Of Technologies Using Fuelwood VII-218
    Option 5: Decrease Production of Disposable Forest Products VII-218
    Substitute durable wood or non-wood products for high-volume disposable uses of wood VII-219
    Expand recycling programs for forest products VII-220
  Increase Supply of Forested Land and Forest Products VII-220
    Option 1: Increase Forest Productivity: Manage Temperate Forests For Higher Yields VII-220
    Option 2: Increase Forest Productivity: Improve Natural Forest Management of Tropical Little-Disturbed And Secondary Forests . . VII-222
    Option 3: Increase Forest Productivity: Plantation Forests VII-224
    Option 4: Improve Forest Harvesting Efficiency VII-228
    Option 5: Expand Current Tree Planting Programs in the Temperate Zone VII-229
    Option 6: Reforest Surplus Agricultural Lands VII-231
    Option 7: Reforest Urban Areas VII-234
    Option 8: Afforestation for Highway Corridors VII-235
    Option 9: Reforest Tropical Countries VII-236
    Obstacles to Large-Scale Reforestation in Industrialized Countries VII-241
    Obstacles to Reforestation in Developing Countries VII-243
  Summary of Forestry Technical Control Options VII-244

PART FIVE: AGRICULTURE VII-249

RICE CULTIVATION VII-252
  Existing Technologies and Management Practices VII-253
  Emerging Technologies VII-257
  Research Needs and Economic Considerations VII-258

USE OF NITROGENOUS FERTILIZER VII-259
  Existing Technologies and Management Practices VII-260
    Management Practices That Affect N_2O Production VII-260
    Technologies that Improve Fertilization Efficiency VII-262
  Emerging Technologies VII-263
  Research Needs and Economic Considerations VII-264

ENTERIC FERMENTATION IN DOMESTIC ANIMALS VII-265
Methane Emissions from Livestock VII-268
Existing Technologies and Management Practices VII-269
Emerging Technologies VII-272
Research Needs and Economic Considerations VII-273

FINDINGS

- **Many technical changes are feasible at reasonable economic costs, which can reduce sources of greenhouse emissions. No single technology or small set of technical options offers "a solution" to greenhouse gas emissions.** Only by aggregating the effects of many technical opportunities over a long time can significant reductions in greenhouse gas emissions be achieved. This chapter highlights options which appear to be "relatively cost-effective". **Detailed analysis necessary to quantify total costs of the measures assumed in the scenarios has not been conducted.**

- Improvements in End-Use Energy Efficiency provide the best option for reducing CO_2 emissions over the next few decades. Reductions in energy use would also reduce emissions of CH_4, N_2O, NO_x, and CO. Examples of potential efficiency improvements are:

  -- **Transportation** -- 50 mile per gallon automobiles are technically feasible with currently available technology. Further improvements could increase fuel efficiency to more than 80 miles per gallon. In addition, major fuel efficiency improvements in diesel trucks, rail transport and aircraft are possible.

  -- **Residential and Commercial** -- Accelerated improvements in building shells, lighting, space conditioning, and appliances could reduce energy consumption per square foot by 75% below current levels by 2025 for residences and 50% for commercial buildings.

-- **Industrial Energy** - Advanced industrial processes for energy intensive basic materials, recycling of used basic materials - i.e., steel, aluminum, and glass, cogeneration and improved electric motors can reduce industrial energy use significantly. This is especially important for most developing countries and Centrally Planned Europe where rapid industrial expansion is expected.

- **Reforestation** offers one of the most cost-effective technical options for reducing CO_2 and other gases. Preliminary estimates of the feasibility of large-scale reforestation suggest that with aggressive reforestation programs the current deforestation trend could be reversed and that a significant net increase in forest biomass is possible. An effective program should include both programs to increase forest biomass - such as replanting marginal agricultural lands, improved management of existing forests, tree plantations, and urban planting - and programs to reduce demand for wood where resources are currently stressed. **This could convert world forest management practices from a net source to a net sink for 0.7 petagrams of Carbon/year, or more, by the year 2025.**

- **Elimination of CFCs and related compounds** over the next decade appears technically feasible and cost-effective. Substitutes or process changes now available or under development have been identified to reduce or eliminate almost all applications of CFCs and Halons. Key examples are:

-- Worldwide replacement of CFCs as an **aerosol propellent** with substitutes already in use in the U.S., Canada and Sweden.

-- Replacement of CFC-12 with substitutes (such as HFC-134a or other hydrochlorofluorocarbons) in **mobile air conditioners.**

  - Replacement of CFC **solvent use** with aqueous cleaning in the electronics industry.

  - Replacement of CFC-**blown foam insulation** with other materials or use of alternative blowing agents.

- **Several actions may be possible to reduce greenhouse gas emissions from agriculture.** The magnitudes of the agricultural sources as well as the potential effects of control measures are difficult to quantify. Further detailed research and data collection will be required in order to produce credible estimates. Major agricultural activities of interest are:

  - **Methane emissions from livestock** could be reduced through increases in productivity of livestock systems, and use of methanogenesis inhibitors for beef cattle.

  - **Methane emissions from rice production** may be reduced somewhat through productivity increases, and removal of crop residues. In the long term, improvements in varieties of rice, soil amendments and water management practices could decrease methane emissions.

  - **Biomass burning** associated with agriculture produces N_20, CO and CH_4. Changes in agricultural practices - sustainable agriculture, utilization of crop residues, etc. - are technically feasible which could substantially reduce this source.

-- **N_2O emissions from fertilizer use** could probably be reduced through better placement of the fertilizer, nitrification inhibitors and fertilizer coatings, which may also reduce farming costs and agricultural runoff problems.

- **Near-term reductions in greenhouse gas emissions from electricity generation** are possible through:

  -- **Efficiency improvements** - Improved fossil electricity generation technology, such as advanced combustion turbines and cogeneration, can increase the efficiency of using these fuels by up to 25%. More efficient transmission and distribution, availability or capacity improvements at existing non-fossil power plants (i.e., nuclear, hydro), and changes in electric utility system operation (i.e., dispatching, wheeling across regions or even internationally) can reduce CO_2 emissions by a few percent per kWh of electricity delivered.

  -- **Fuel switching** - Use of more natural gas to displace coal as a fuel for generating electricity could reduce CO_2 emissions by a substantial amount in the near term. The potential of this option is largely dependent on availability and cost of natural gas in the future. Wood, municipal waste, wind, etc. could play a somewhat larger role than they currently play in the near term.

- **Alternative fuels** that do not emit significant amounts of greenhouse gasses could make an important contribution to reducing these emissions in the medium term and could virtually eliminate many categories of emissions over the long term. For widespread use of alternative fuels, important engineering, economic, environmental and social issues must be resolved.

-- **Hydroelectric power** is already making a significant contribution to global energy production. There is significant potential to expand this contribution although environmental and social impacts of large scale projects must be considered carefully.

-- **Biomass energy** is currently being extensively utilized, particularly in developing countries. Current and emerging technologies could vastly improve the efficiency of that use. More advanced technologies, especially for conversion of biomass to gaseous and liquid fuels and electricity could become economically competitive within a decade. Measures to increase biological productivity are also under study. These advances would allow biomass to provide a much larger share of global energy services over the long term, particularly in developing countries. Environmental and social issues of large scale biomass include land use, competition with food production, particulate and organic emissions, etc.

-- **Solar energy** offers a large range of options. Direct use of solar thermal energy either passively or in active systems is already commercially available for water and space heating applications in many regions. These applications could be expanded considerably in the near to medium term. Solar thermal concentrating technologies are being widely tested for power generation or industrial process heat. Solar photovoltaic (PV) cells are economically competitive for some remote power generation needs, especially in developing countries. If current research and testing succeeds in lowering the cost in the next decade, solar electricity generation could play a major role in meeting energy needs in the next century.

-- **Geothermal energy** resources are extensive and widely distributed. Systems are commercially available for electricity generation, and over 7 gigawatts of capacity are currently in operation worldwide. Technologies are improving and being demonstrated rapidly. It may be possible to expand this energy source significantly in future.

-- **Wind energy** systems are currently commercial in some applications and locations. In recent years engineering advances have resulted in reductions in cost and improvements in performance. Assuming this trend continues, wind energy can play a larger role in future energy production.

-- **Nuclear fission** is a technology which is currently widely used and growing in its contribution to global energy supply, due to the completion of power plants ordered during the 1970s. High cost and concerns about safety, nuclear weapons proliferation and radioactive waste disposal have brought new orders to a halt in most countries. It is technically feasible to expand the contribution of this energy source beyond what is currently projected in the future, if these problems are resolved.

- **Emission controls** - Control technologies are currently available to reduce CO from automotive and industrial sources and NO_x produced by power generation at relatively low cost. Other technologies are available which remove larger fractions of these pollutants but at higher cost. Emerging control technologies and combustion technologies with inherently lower NO_x emissions are being tested and could reduce NO_x emissions drastically at lower cost. In a few very limited situations (i.e., enhanced oil recovery) CO_2 recovery from power plant flue gas may be economic.

- **Methane emissions from coal seams, natural gas production and landfills can be reduced.** Currently minor emissions from coal production and landfills are projected to grow in future. Natural gas (primarily methane) is sometimes vented and often flared in conjunction with oil production. Technologies exist for economically recovering this methane and utilizing it for energy production, thereby partially augmenting natural gas supply.

- **Aggressive research programs** may be the most important policy option **for the long run.** Resolution of several key technical issues could vastly expand the economically attractive options for reducing greenhouse gas emissions in the next century. Some important examples are:

    -- **Improved characterization of sources and control options** in several areas would allow better policy and research planning decisions to be made. Sources of N_20 and CH_4 are poorly understood at present. Field measurement and data collection work are needed to improve understanding of the potential role reductions in these emissions could play in an overall climate stabilization strategy. Detailed cost analysis is also needed for most of the technical reduction options identified to support policy decisions in future.

    -- **Solar photovoltaic** technology has been improving rapidly over the last decade. Continuing or accelerating this progress could bring this technology into widespread commercial viability early in the next century.

    -- **Biomass conversion** technologies currently exist which could make substantially greater contributions. Commercial demonstrations of some existing technologies and additional research on advanced biomass conversion technologies and improvements in biomass productivity could greatly expand the role of biomass energy.

-- **Nuclear fission** does not currently appear viable in many countries because of safety, waste disposal, proliferation and cost concerns. Research is underway in several countries to develop and demonstrate "second generation" fission technologies which reduce cost and safety concerns. The establishment of waste disposal plans acceptable to society is also an area of intense study in several countries already committed to nuclear fission. Satisfactory resolution of these problems could expand the role of nuclear fission in future decades.

-- **Energy storage** technology could play a crucial role in integrating intermittent technologies such as solar and wind into energy supply systems. A number of promising concepts are currently under study. Accelerating research and testing to reduce cost and improve performance of storage technologies for electrical energy could greatly expand the potential roles of some alternative energy sources.

-- **Hydrogen energy** systems offer a long term potential for reducing or eliminating CO_2 emissions, if the hydrogen is produced from non-fossil energy inputs. Hydrogen is not a primary energy source but rather an "energy carrier," an intermediate form like electricity. As an energy carrier, it can help resolve some of the energy storage issues with renewables and substitute in some existing fossil fuel applications. Research needs include improved conversion processes using solar, hydroelectric, nuclear, wind, or other renewable energy inputs. Additional concerns include transmission and storage, and applications to transportation, space heating, industrial process and other end uses.

- **Selected research in energy efficiency** could be helpful in accelerating the rate of improvement. Industrial technology, for example, could be developed to allow major increases in the standards of living in developing countries and Centrally Planned Europe without the enormous increases in CO_2 emissions which accompanied this development in the OECD. A major cooperative research effort to adapt advanced technologies under development in the OECD to the particular constraints and needs of the rapidly industrializing areas could be effective.

- **Agricultural research** to identify and develop alternative rice production systems which reduce the production of methane could play a significant role in a long term solution to the greenhouse problem. Similarly, improvements in productivity and other technological options for reducing methane emissions from **domestic animals** (cattle, sheep, etc.) are possible. Concentrated research in these areas could make a major long term contribution to greenhouse emissions reductions.

INTRODUCTION

This chapter describes the substitute technologies and other means by which greenhouse gas emissions could be reduced relative to the scenarios described in Chapter V. A range of policies that might be used to promote such reductions are described in the next two chapters, which address domestic and international issues.

The preceding chapters discuss the diverse sources and economic activities responsible for greenhouse gas emissions. It should therefore not be surprising to find that there are an equally diverse array of methods for reducing greenhouse gas emissions. The primary means of accomplishing this goal is the **development and use of technologies** that reduce energy requirements (i.e., improve energy efficiency), use less carbon-intensive fuels, or that replace or reduce emissions of other greenhouse gases. In addition to this technological approach, there are also several areas in which **management strategies** are the means of reducing greenhouse gas emissions, particularly with respect to the buildup of gases resulting from some agricultural practices and forest resources.

The Relationship Between Technical Control Options and EPA's Modeling Results

As noted in Chapter V, the single most important determinant of greenhouse gas emissions is the level of energy demand and the combination of sources used to supply that energy. Given the dominance of fossil fuels as a source of greenhouse gas emissions, technologies to reduce use of fossil fuels must play a central role in any effort to stabilize concentrations. Fossil-fuel-based technologies supply over 70 percent of global primary energy needs in the No Response scenarios. A major focus for policies to reduce emissions, as discussed in Chapters VIII and IX, must accordingly be to promote demand-side measures that reduce total energy demand and supply-side measures that promote less carbon-intensive fuels. Technologies to achieve these goals are therefore a major focus of this chapter.

The No Response scenarios assume substantial efficiency gains will occur due to technological innovation and market forces, as discussed in Chapter V. The demand-side measures discussed in this chapter illustrate how this assumed efficiency improvement might occur as well as improvements incorporated into the Stabilizing Policy scenarios and more rapid improvements analyzed in Chapter VIII.

The Economics of Control Options

The uncertainties associated with many of the options described in this chapter preclude detailed assessment of costs. The primary focus of this review is to identify techniques that appear promising although for cost or other reasons, they may not be widely-accepted in today's markets. This is necessary given that global climate change is a long-term problem that may require development of new energy sources and other significant technological breakthroughs. Current prices also may be a misleading basis for assessment since climate change is potentially a major cost not currently reflected in the cost of goods and services; as discussed in Chapter VIII, it may be desirable to rectify the absence of a market price for the risk of climate change through the imposition of carbon fees or other policies, in which case currently more expensive options may become more competitive.

The price of some options is also difficult to evaluate simply because the absence of a market for reducing the risk of climate change has meant relatively little effort toward research and development. The importance of creating a market incentive to improve technology and reduce costs is demonstrated from the rapid recent development of substitutes for CFCs discussed in this chapter. Until such time as it became apparent that environmental regulation would create a market for CFC substitutes, industry reported that there were few feasible options at any price. More recently, an intensely-competitive race to commercialize substitutes has begun around the world.

While a detailed economic analysis of the options discussed in this report is impractical, it is worth noting that many of the control options described in this report are economically justified or nearly so today, even based on current costs. This is particularly true in the context of measures to improve energy efficiency, where substantial opportunities for cost saving investments exist despite recent progress, as discussed in Chapter VIII.

The Role of Long- and Short-Term Options

In the time frames considered in this report, long-term options become critical. In order to substantially reduce the concentration of greenhouse gases, new sources of energy supply and dramatic improvements in efficiency will have to assume a significant role. However, there is also much that could be done to reduce greenhouse gas emissions over the next decade by improving energy efficiency, making greater use of natural gas, reducing use of CFCs, and promoting reforestation.

While this current generation of techniques will not be sufficient to stabilize greenhouse gas emissions several decades hence, efforts to adopt such technologies are nevertheless likely to be exceedingly valuable for several reasons. First, reducing the rate of growth in emissions now could make it easier to stabilize concentrations in the future because of the long atmospheric life of these gases. Second, short-term strategies are often intermediate steps toward long-term strategies, e.g., currently-available efficiency improvements will facilitate still greater future efficiency improvements. Finally, the incentives necessary for longer-term strategies, such as emission fees on carbon-intensive fuels, will generally be consistent with short-term strategies.

Over the long term the most important options are advanced non-fossil energy technologies, possibly combined with major breakthroughs in end-use technology that would drastically reduce energy requirements. Also, changes in agricultural and forest management technologies could become important. In addition to the incentives that may flow out of short-term strategies, it is important in the short term to promote national research and development by governments and the private sector toward identifying and advancing promising long-term technologies.

Control Techniques and Worldwide Emissions

As the modeling results make clear, the U.S. is likely to account for a declining share of future greenhouse gas emissions. Stabilizing concentrations will require control options applicable to the needs of other countries, particularly developing countries with very different resources. Some technologies, such as more efficient lighting, are relevant to virtually all parts of the world, but other needs vary considerably. This chapter therefore discusses improved cookstoves, strategies for arresting tropical deforestation, and other options of particular relevance to developing countries. Table 7-1 illustrates some of the promising options for various regions and time horizons.

Organization of this Chapter

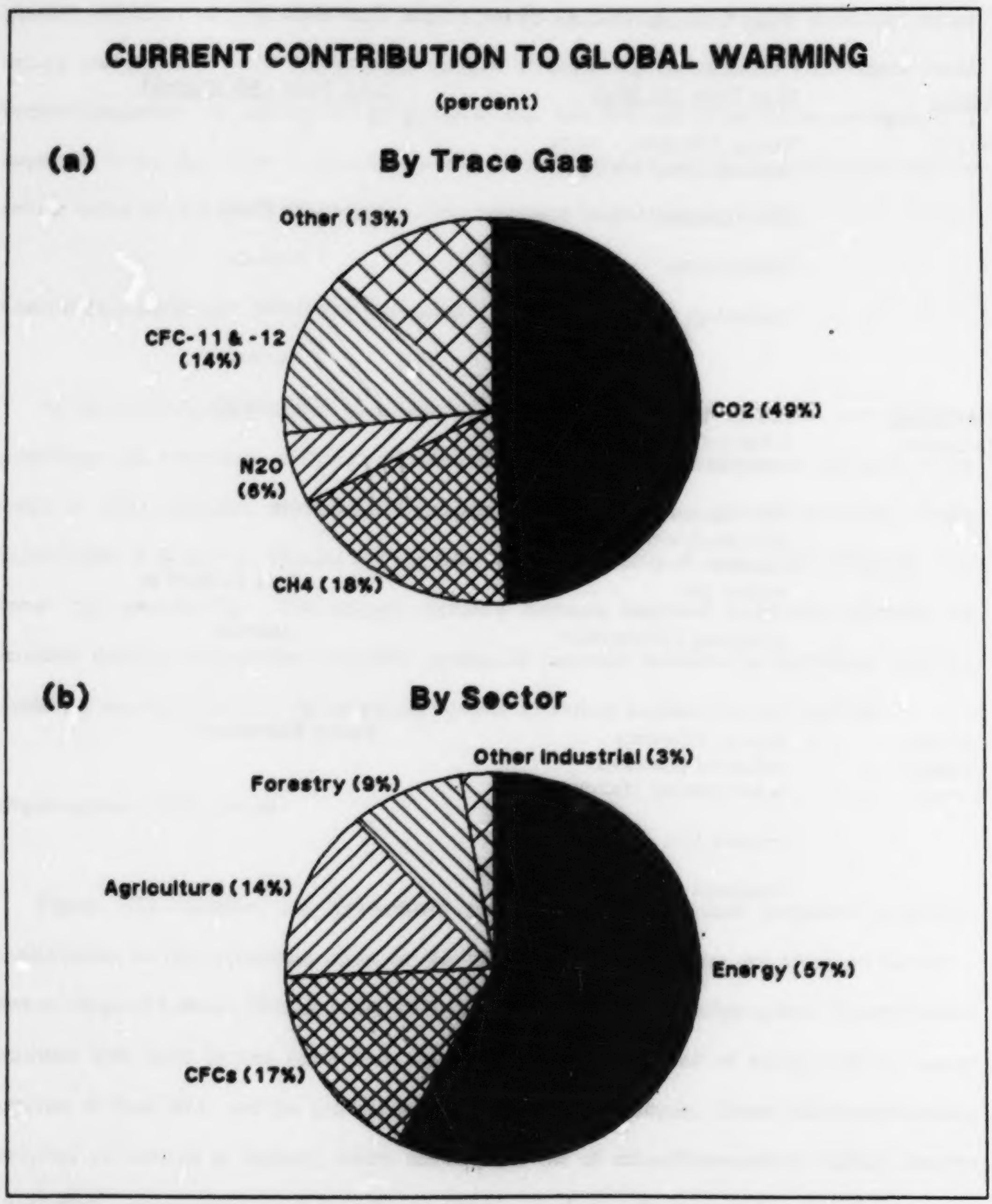
Figure 7-1a identifies the "greenhouse gases" and illustrates their estimated percentage contributions to the greenhouse effect in the 1980s. All of these gases are produced through a diverse range of human activities, which we have classified into five broad categories. Energy-related activities have been broken down into two categories: "applications" of energy, that is, energy services, or "end uses," and the production of energy, or energy supply. Other emissions-producing activities are related to industry, which includes the use of chlorofluorocarbons (CFCs), forestry (particularly deforestation), and agriculture. Often a single broad category of activity--fossil energy

TABLE 7-1

Key Technical Options By Region and Time Horizon

Region	Near Term (by 2010)	Long Term (All Regions)
OECD	Energy Efficiency - autos, lighting, space heating CFC Controls Reforestation Technology Development	**Alternative Fuels** Biomass Solar Nuclear Hydrogen **Agriculture** Rice Production Animals **Forest Plantations**
Developing Countries	Energy Efficiency - industrial processes, transport Low-Carbon Energy hydroelectricity biomass natural gas Reversing Deforestation	
Centrally Planned Europe	Energy Efficiency - industrial processes, space heating, transport Natural Gas Nonfossil electricity	

FIGURE 7-1


CURRENT CONTRIBUTION TO GLOBAL WARMING
(percent)
(a)
By Trace Gas
Other (13%)
CFC-11 & -12 (14%)
N2O (6%)
CH4 (18%)
CO2 (49%)
(b)
By Sector
Other Industrial (3%)
Forestry (9%)
Agriculture (14%)
CFCs (17%)
Energy (57%)

consumption, deforestation, for example--contributes to several of the gases of concern. Figure 7-1b shows the proportion that the major categories of human activity contribute to global warming.

Because of the enormous amount of information presented in this Chapter (in truth, a separate chapter could be devoted to each major source category discussed here), we have departed somewhat from the format used throughout the rest of this Report to Congress--to make it easier for the reader to follow the discussion. Thus, the remainder of this chapter is divided into five parts.

Energy use causes, in different proportions, emissions of five important gases: carbon dioxide (CO_2), carbon monoxide (CO), methane (CH_4), nitrous oxide (N_20), and nitrogen oxide (NO_x). Energy use is integrally linked with virtually all forms of economic and recreational activity within industrialized countries. In developing countries current biomass energy use contributes to greenhouse gas emissions, and potential increases in commercial energy use could be the largest source of increasing greenhouse gas emissions in the future.

Thus, evaluation of the options for reducing greenhouse gas emissions from energy use must begin with a systematic analysis of all aspects of energy use. Although there are "end-of-pipe" control options for removing some of the relevant emissions from energy use while leaving the basic process intact, the potential impact of such approaches is very small relative to the magnitude of the overall problem. A strategy designed to significantly reduce the warming potential of energy-related activities must incorporate major reductions in fossil energy consumption.

Part One of this chapter reviews the basic applications for which energy is ultimately used and the opportunities for reducing greenhouse emissions at the point of end use. Part Two reviews energy supply and conversion activities and related opportunities for reducing emissions. This includes improvements in efficiency in energy conversion and distribution, and potential for increasing supplies of non-fossil energy sources. Also discussed are reductions in emissions of CH_4 from coal mining and natural gas production and distribution.

In Part Three we discuss technical options for controlling emissions from industrial activities. Non-energy industrial activities contribute to greenhouse warming in three significant ways. First, and most important, industrial activities are the source of all CFC emissions. As discussed in Chapter IV and IX, an international process is already underway to reduce global emissions of CFCs because of their role in depleting the stratospheric ozone layer. This chapter discusses the technical potential for reducing CFCs further than required under the current protocol.

A second source of industry-related emissions are landfills, which produce emissions of methane (CH_4). This source category represents a small portion of the total methane emissions, but emissions from this source could increase rapidly in the future. Finally, production of cement produces CO_2 as a process emission (in addition to CO_2 produced by energy consumption). This again is a small component of total CO_2 emissions currently, but the percentage contribution from cement production has been growing rapidly in recent years.

In Part Four, we discuss options related to forest management practices (resulting in a net annual loss of biomass), which account for a significant share of emissions of CO_2 and CO as well as some portions of other gases. It should be noted that the importance of forestry is greater than its percentage share in Figure 7-1 implies. Forests are the only category that, over time, can be shifted from a source to a major sink for carbon. It is technically possible, though by no means simple, to reverse the long-term trend of global deforestation and to begin increasing the amount of forested lands. There are several components to reforestation strategies that need to be considered. For example, reductions in demand for forest products (e.g., fuelwood) in some areas may be necessary to relieve the pressures that have caused deforestation in recent years.

Agricultural activities are an important source of CH_4, N_2O, NO_x, and CO. The principal activities of interest are rice production, enteric fermentation in domestic animals (primarily cattle, sheep, etc.), fertilizer use, and biomass burning. In the final section of this Chapter, Part Five, we discuss the technical options for reducing emissions resulting from these activities. It is apparent that considerable flexibility exists, particularly in the long term, to alter agricultural practices in the specific categories that constitute the large emitters, but the technical potential is difficult to quantify.

In general, most of the research and analysis of agriculture to date has focused on opportunities for improving productivity. Productivity improvements should automatically lead to some reductions in greenhouse gas emissions per unit of output; however, this relationship is not well-quantified. Additional options for reducing emissions, beyond productivity changes, can be envisioned for each of the specific categories mentioned, though, again, very little work has been done as yet to quantify their potential effects and costs.

Limitations

In this review the information presented, although somewhat detailed, can only begin to illustrate potential technical options that currently appear most promising. The analysis also highlights the uncertainties and need for further study of many options. In some areas, particularly techniques for reducing emissions from agricultural sources, the impact of specific technologies cannot be estimated at present. However, in general, the uncertainties that exist concerning the means of achieving emission reductions are much less, or are likely to be much more easily resolved, than the uncertainties that exist concerning the rate of warming, change in climate, and the ultimate effects of an increase in greenhouse gas concentrations. While some currently emerging technologies may not fulfill current expectations, the diversity of opportunities suggests we can emphasize the development and use of technologies that are relatively less-intensive sources of greenhouse gas emissions if we choose.

The source of most of the uncertainties discussed in this chapter is the difficulty of predicting future technological developments. Many of the options that may have the greatest impact on the buildup of greenhouse gases, such as the development of new engine technology for cars, new designs for nuclear plants, and the use of hydrogen as a substitute for liquid fuels, are long-term possibilities that require substantial further research. It is important to recognize several key limitations:

- The discussion cannot deal exhaustively with the tremendous range of technical options that have been identified for energy efficiency improvements and fuel substitution and for industrial emissions reductions, as well as for forest management and for implementing changes in agricultural practices.

- Because of the limited information available, but even more because of the extensive scope of this study--both in the range of emitting activities and the global diversity of emissions--it was not possible to provide detailed quantification of expected emissions reductions and costs for many of the technical options discussed.

- Much data development and detailed analytical work remains to be done. A more detailed technical assessment has been mandated by the congress. This study is beginning now and will be completed in 1989 by the U.S. Department of Energy and EPA.

- As discussed in Chapter V, scenarios are constrained by current expectations about types of services and economic activities demanded by consumers. The control options presented are intended to produce the same types of goods and services--electricity, lighting, transportation, space heating, etc.--

but with a lower level of greenhouse gas emissions. These technologies and strategies are therefore generally consistent with current lifestyles and consumer preferences. However, some of them are likely to increase or lower costs that could lead to changes in demand. This may result in underestimating the effects of some technical options and strategies on future greenhouse gas emissions.

- The No Response scenarios used in this report assume a considerable amount of efficiency improvement due to technological innovation and market forces. As discussed in Chapter V, the energy use in these scenarios is substantially lower than some other reference projections (e.g., DOE/NEPP; see **CHAPTER V**). If energy use is higher than reflected in the No Response Scenario, then the impact of policies that promote energy efficiency, such as those identified in this chapter, could be much more effective in reducing energy consumption than indicated here.

- Discussions of the potential performance of technical options in this chapter are often based on engineering design calculations, prototype performance, laboratory results, etc. Achievable performance in practice may be less since mass production often requires some engineering compromises relative to laboratory or prototype specifications. Also, performance of technology in use often deteriorates somewhat from design or new product performance. On the other hand, currently unforeseen developments may improve performance beyond levels estimated today.

- This chapter identifies and attempts where possible to quantify **technical potentials** for reductions in greenhouse gas emissions. Even where technical options appear economically attractive on a life-cycle basis, there are generally institutional, behavioral, and policy constraints that currently operate to limit their penetration. The portion of identified technical potential that can be achieved in practice is largely a function of the availability and effectiveness of policy options, as discussed in **CHAPTERS VIII and IX.**

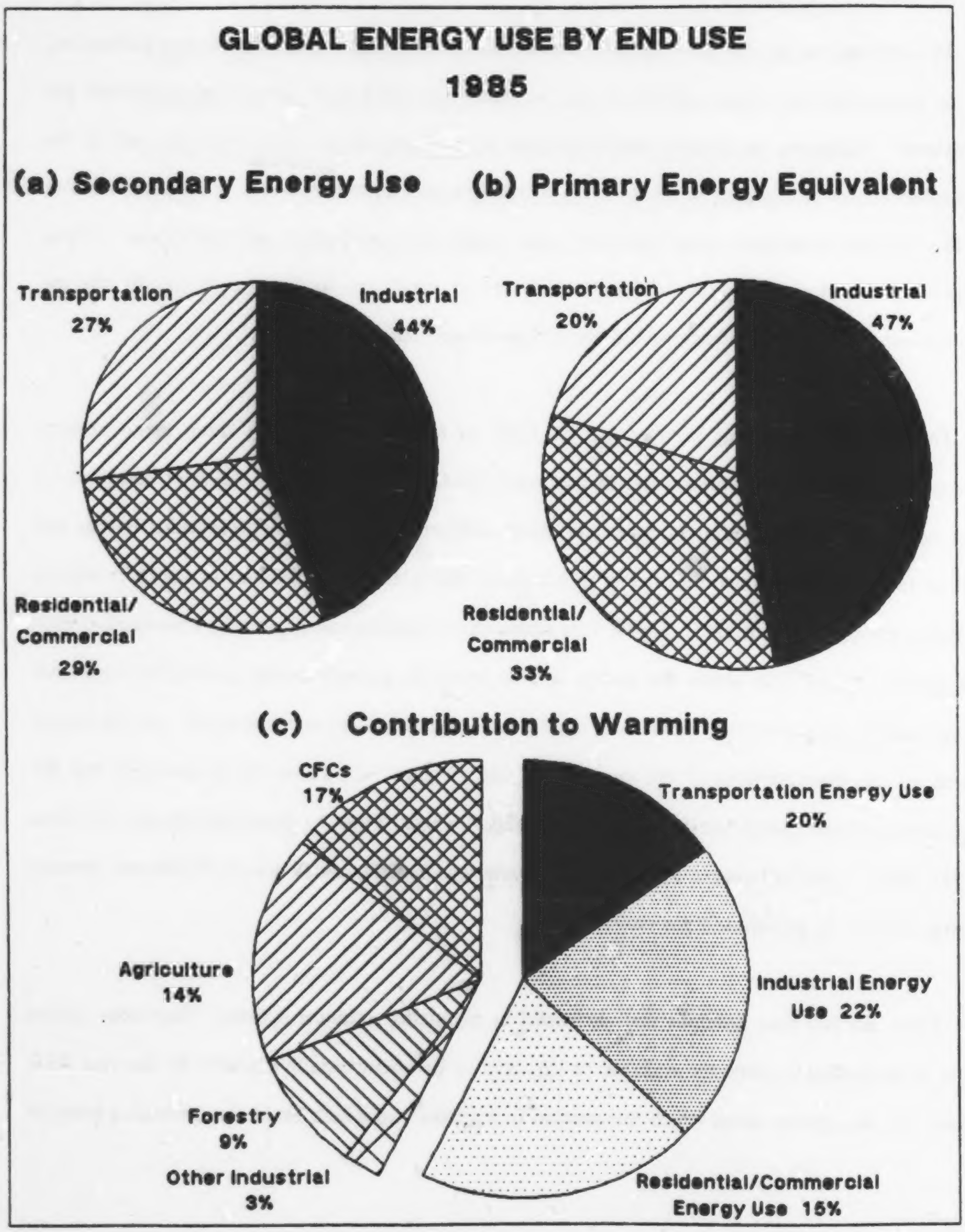
PART ONE: ENERGY SERVICES

The services that energy provides (called end-uses), such as lighting and fuel-driven locomotion, are an integral part of human society and, at the same time, the largest category of greenhouse gas emissions. While the production and conversion of primary energy (e.g., coal, oil, gas) is the immediate source of a large portion of energy-related greenhouse gas emissions, it is the applications of this energy to provide specific services that justify this production and conversion. Thus, minimizing the energy required in various end-uses or using non-fossil fuels in specific end-use applications can reduce production- and conversion-related emissions as well.

For convenience, energy services are classified as belonging to one of three major sectors: transportation, residential/commercial, and industrial (including agriculture). Each of these sectors uses energy in distinctly different ways and offers different opportunities for reducing energy use and/or shifting to alternative fuels. Figure 7-2 shows the relative contributions of the three sectors to global energy use as of 1985. Figure 7-2a shows the secondary energy actually consumed at end-use points. Figure 7-2b shows the energy use by sector in primary energy production equivalent terms; that is, the production, conversion, and transmission losses are ascribed to the end-use sectors based on the characteristics of the energy they use. Figure 7-2c shows the proportions that the equivalent primary energy use for these three categories contributes to global greenhouse emissions in the 1980s. The differences are due to the variations in unit contributions of different primary energy sources to greenhouse gas emissions.

There are two time horizons that are useful in discussing technical options. Near-term options refer to technologies currently available or expected to be commercially available by the year 2000. These are the options about which information is available and which could also provide a basis for

FIGURE 7-2


GLOBAL ENERGY USE BY END USE
1985
(a) Secondary Energy Use
Transportation 27%
Industrial 44%
Residential/ Commercial 29%
(b) Primary Energy Equivalent
Transportation 20%
Industrial 47%
Residential/ Commercial 33%
(c) Contribution to Warming
CFCs 17%
Transportation Energy Use 20%
Agriculture 14%
Industrial Energy Use 22%
Forestry 9%
Other Industrial 3%
Residential/Commercial Energy Use 15%

near-term policy action. Long term refers to options that are not expected to be available until after 2000, in some cases well after.

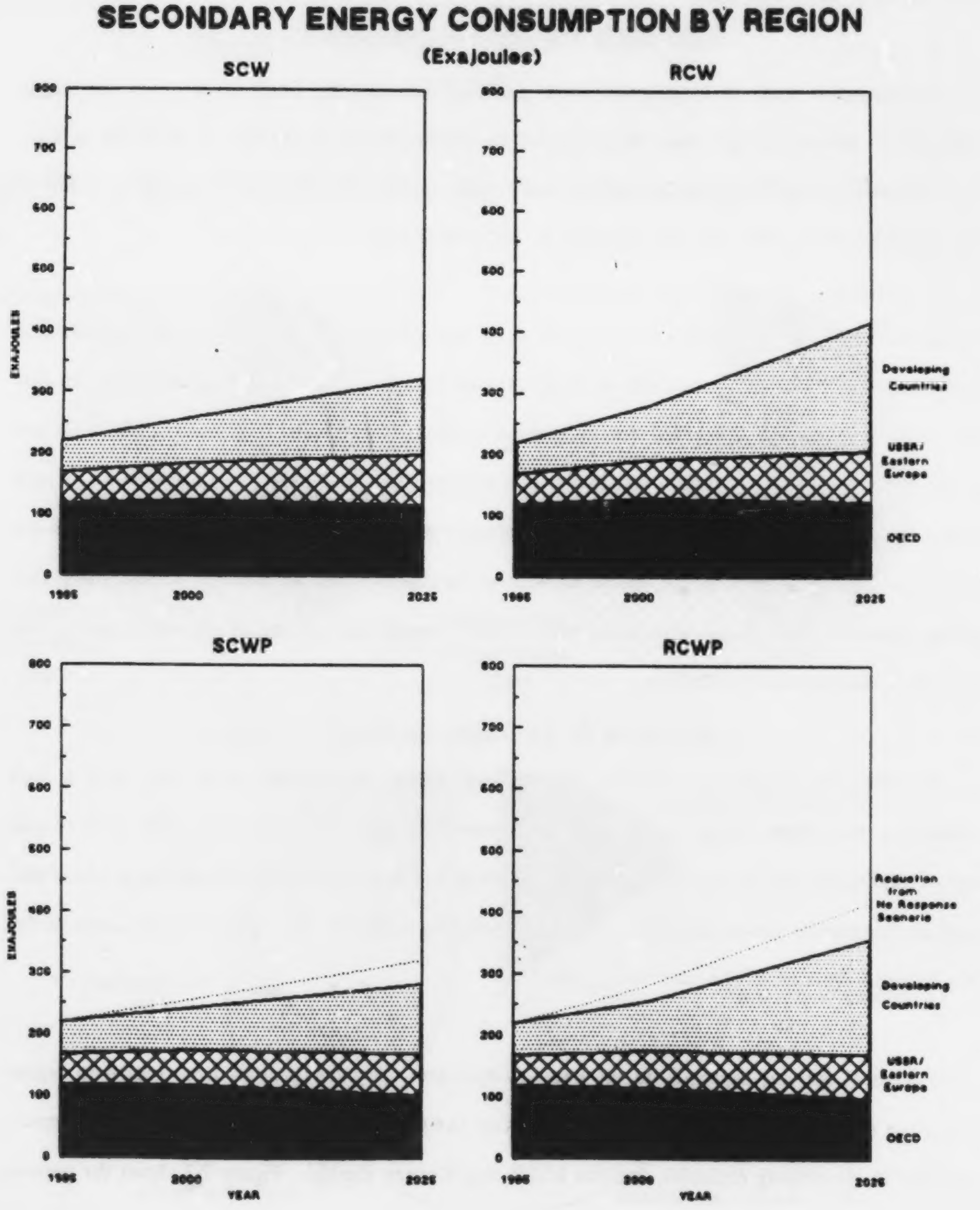
An attempt is made to hypothesize about potential technological developments over the longer term and to discuss the role research could play in accelerating the availability of advanced options. Some of these technologies are speculative and require additional research. They are included in the analysis because they have the potential to play major roles in the long run.

In discussing global energy use patterns, it is important to distinguish between modern and traditional energy forms, particularly in understanding energy use in developing countries. In this discussion modern or commercial energy is used to describe all fuels and energy forms that are priced and sold in energy markets (or, in the case of centrally-planned economies, accounted for and valued in national economic planning). In this category are virtually all of the fossil fuels, which are the major source of greenhouse gases, as well as electricity from all sources. Readily-available energy statistics deal almost exclusively with modern energy and accurately represent energy use patterns in industrialized countries.

However, in developing countries the modern energy transactions alone can give a very misleading picture of energy use. Traditional energy is used to mean fuels such as firewood, agricultural waste, and animal waste that are gathered and used informally without being priced and sold in commercial energy markets. In many developing countries this type of energy accounts for a substantial fraction of the total energy used.

Technical options, especially in the near- to mid-term, vary substantially from region to region and often among individual countries. We focus on the U.S. explicitly, and three blocs of countries: the OECD, developing countries, and the USSR and Eastern Europe. Figure 7-3 shows the pattern

FIGURE 7-3



SECONDARY ENERGY CONSUMPTION BY REGION

(Exajoules)

of energy consumption for these blocs of countries over time under both the No Response Scenarios (SCW and RCW) and the Stabilizing Policy Scenarios (RCWP and SCWP).

The industrial market economies, the members of the Organization for Economic Cooperation and Development (OECD), have many similarities in terms of economic activities and resources, and hence are discussed as a group. As shown in Figure 7-3, energy use in these countries is relatively high but not expected to grow significantly; rising incomes are devoted increasingly to products that do not require significant energy inputs.

The developing countries are vastly different from industrialized countries both in current levels and types of economic activities and available resources. As shown in Figure 7-3, energy use in the developing countries grows significantly in the scenarios, but there is great uncertainty about the rate of growth. Depending on their rate of development, energy use in these countries increases by a factor of 2.5 to 4 by the year 2025.

The USSR and Eastern Europe share with most developing countries a much greater emphasis on government intervention in economic planning and industrial activities than do OECD countries. On the other hand, these countries have massive and, in many ways, technologically-sophisticated industrial infrastructures that are much more similar to those of the OECD countries than they are to the industrial infrastructures of most developing countries. Energy use in Eastern Bloc countries (and associated greenhouse gas emissions) has been growing rapidly and, as shown in Figure 7-3, is projected to grow in the future. While less is known about the technical potential to reduce emissions in these countries, it is generally believed that very substantial improvements can be made in energy efficiency.

Figure 7-4 shows how secondary energy use by end-use category changes in the No Response scenarios (SCW and RCW) and the two Stabilizing Policy scenarios (SCWP and RCWP). Overall, secondary energy use in 2025 is 13-15% lower in the Stabilizing Policy scenarios; one reason for the limited reductions in energy use is that significant improvements in energy efficiency are assumed to occur in the No Response scenarios. The Rapid Reduction Scenario described in Chapter VIII illustrates some of the additional potential. In that case total secondary energy use was reduced by 20% from the RCW scenario by 2025. As discussed in this section, these are very conservative reductions relative to the technical potential. In both policy scenarios, energy use in transportation decreases the most as a result of the introduction of fuel-efficient, light-duty vehicles and the relatively rapid turnover of the vehicle stock.

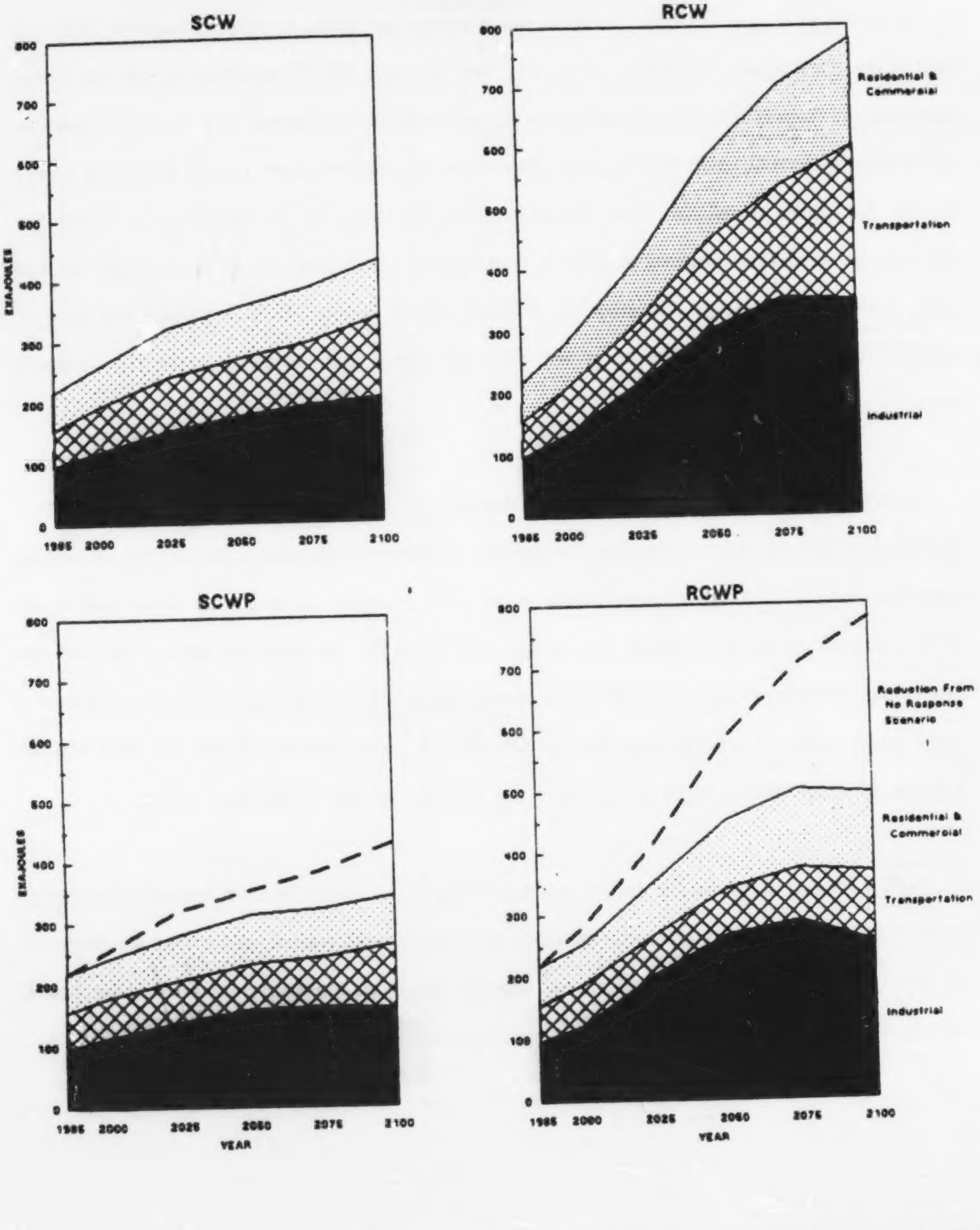
Residential/commercial energy savings are smaller, reflecting the longer turnover times. The industrial sector represents the largest current component of energy use and the largest portion of projected growth in the No Response scenarios. Despite this, the reductions in industrial energy consumption in the Stabilizing Policy scenarios are relatively modest, a reflection primarily of the diversity of the industrial sector and the difficulty in designing broad policy assumptions that will affect this sector in the modeling analysis. There are clearly large opportunities for energy savings in the industrial sector, as discussed below.

TRANSPORTATION SECTOR

Transportation currently consumes approximately 27% of global modern energy use. As shown in Figure 7-4, it accounts for 20-30% through 2025 in the No Response Scenarios. Virtually all of the energy used in transportation is derived from oil. In 1985 in OECD countries, energy used for transportation accounted for about 23% of all energy consumed (27% in the U.S.), expressed as

FIGURE 7-4

END-USE ENERGY DEMAND BY SECTOR
(Exajoules)



primary energy equivalents. As a share of secondary energy consumption, transportation accounted for about 34% in the OECD, about 97% of which was oil (U.S. DOE, 1987b).

As shown in Figure 7-5, global transportation energy use grows by 50-65% between 1985 and 2025 in the No Response scenarios. In the U.S. and the other OECD countries, in both the Slowly Changing and Rapidly Changing World scenarios, improvements in efficiency as a result of economics and technological innovation slightly more than offset the relatively slow rate of growth in energy services (i.e., miles travelled). The OECD accounts for over 65% of transportation energy use currently, but their share declines in absolute terms and as a percentage of the total. In the last few years, transportation energy efficiency has declined slightly in the OECD. If this trend were to continue, OECD transportation energy use could be higher than indicated in the No Response scenarios.

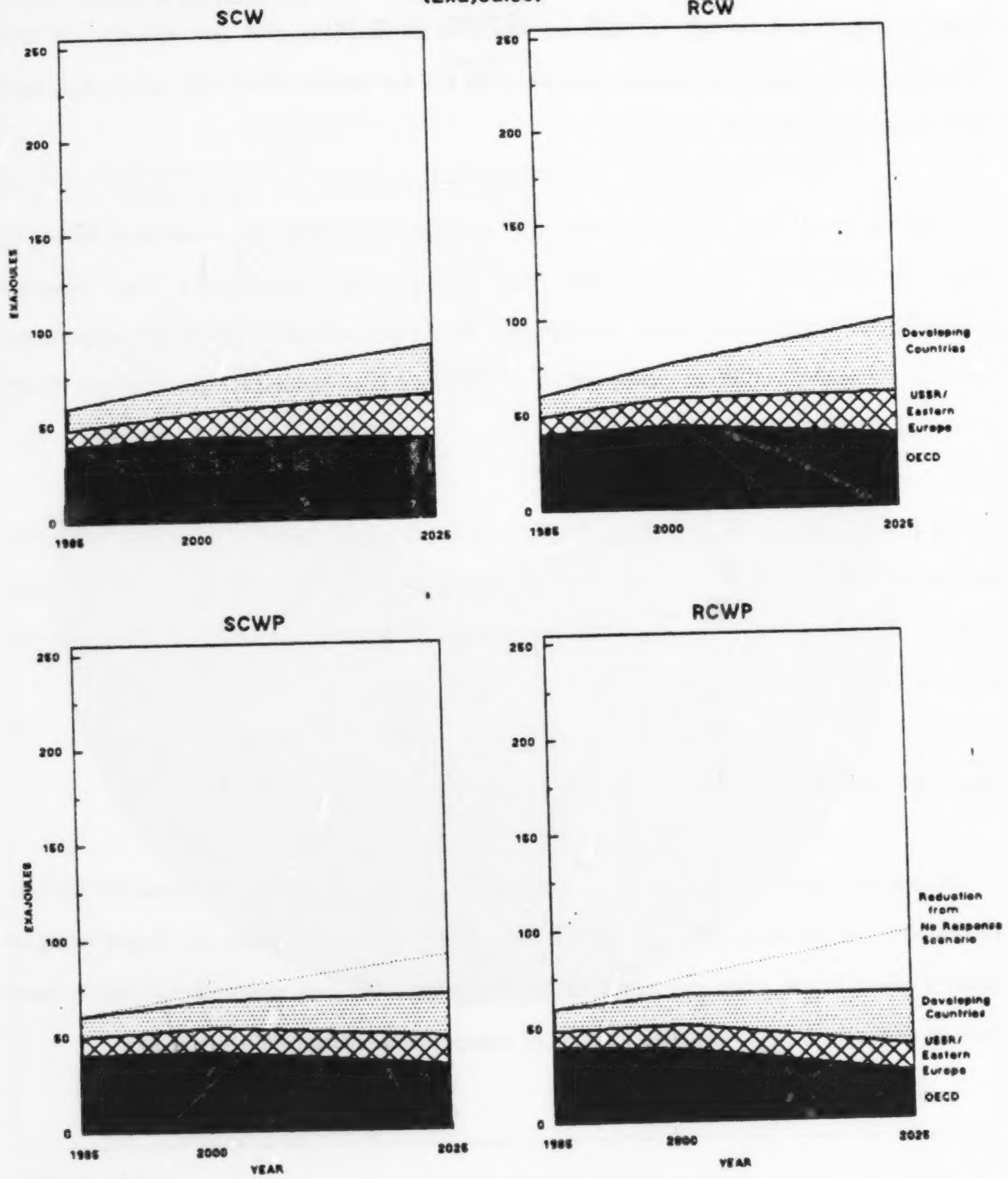
In the USSR and Eastern Europe, transportation energy use increases rapidly, more than doubling by 2025 in the No Response scenarios. Transportation energy use in the developing countries grows at a roughly equivalent rate in the SCW scenario, but at a much higher rate in the RCW scenario, reaching 3.5 times its current level by 2025. In both the Soviet bloc and the developing countries, freight transport and passenger mass transit (rail, bus) currently account for a much larger share of total energy than in the OECD. The explosive growth in both regions, however, is largely due to rapid expansion in the number and use of light-duty vehicles.

Figure 7-5 also illustrates the impact that Stabilizing Policies could have on transportation energy use in 2025. Overall energy efficiency improves significantly in all regions, and energy use decreases by a large percentage. While total energy demand decreases, alternative fuels are more heavily utilized, thus reducing the amount of fossil fuels used to produce transportation services.

FIGURE 7-5

TRANSPORTATION ENERGY USE BY REGION

(Exajoules)



In industrialized countries it is likely that the private automobile will continue to be the primary means of transportation in the near future. Fortunately, there are near-term opportunities for improving the efficiency of this mode of transportation. Near-term improvements in efficiency of freight transport and aircraft will also be cost-effective over the next few decades. A few industrialized countries (e.g., Canada, New Zealand) are also pushing ahead with major alternative fuels programs in the near term.

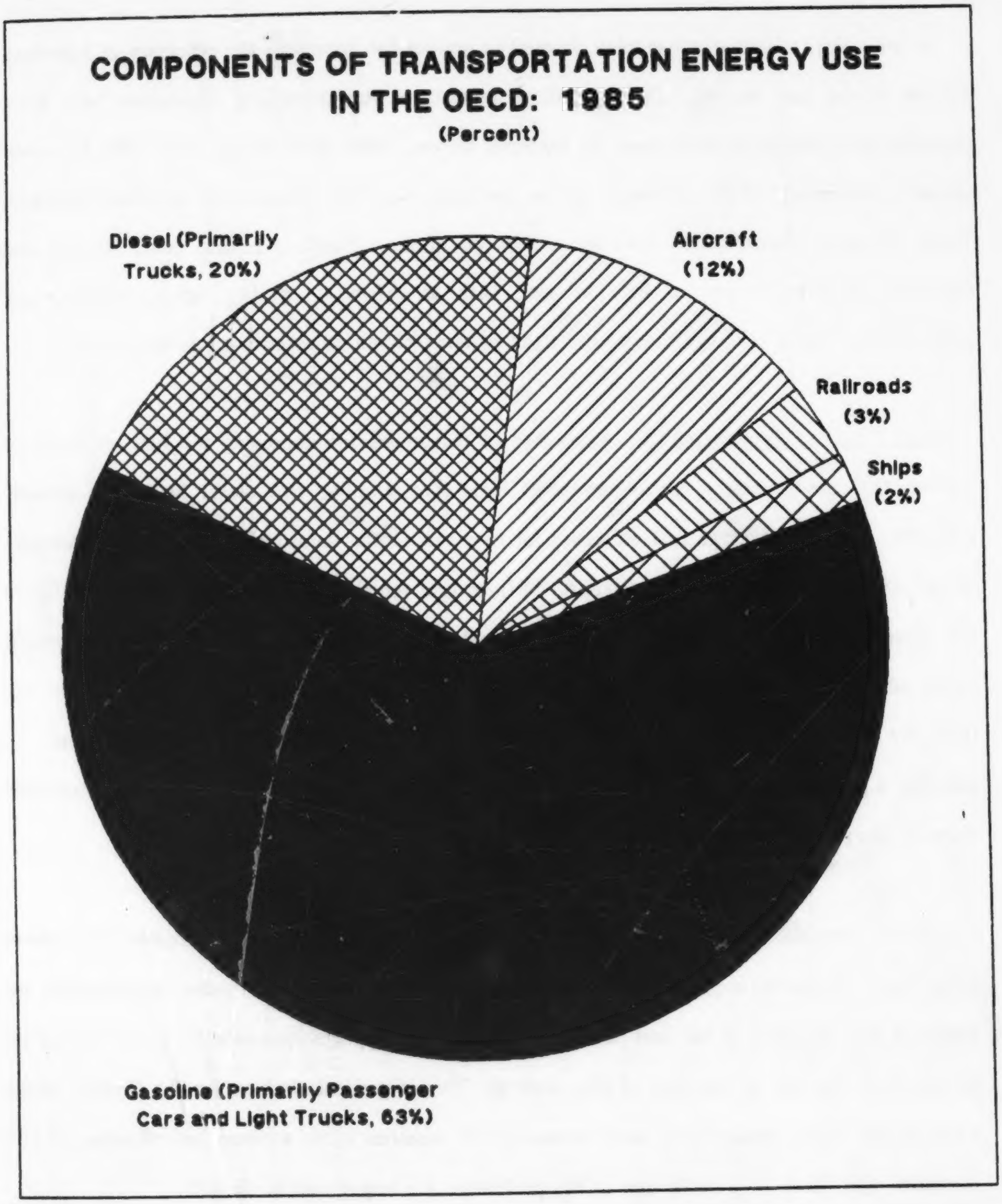
Over the longer term, additional reductions in energy consumption may come from shifting to more efficient modes of transportation and substitutes for transportation (e.g., advanced communication technologies). Also, increasing the use of non-fossil-based fuels in the transportation sector is essential in order to greatly reduce or eliminate greenhouse gas emissions (See PART TWO: ENERGY SUPPLY).

In developing countries and the Soviet bloc, transportation currently accounts for a smaller percentage of total energy use. (In some African countries, however, the percentage is much higher.) However, in the future, as economies expand and incomes rise in these regions, the potential exists for explosive growth in transportation energy use.

Near-Term Technical Options: Industrialized Countries

Within the transportation sector, light-duty vehicles, mainly passenger cars, account for the bulk (about 63%) of current energy use (Figure 7-6). Other major contributors are freight transport vehicles (diesel trucks, ships, and railroads), accounting for about 25%, and aircraft, primarily those used in passenger travel, accounting for 12% of transportation energy.

FIGURE 7-6



(OECD, 1987)

Light-Duty Vehicles

A great deal of attention has been devoted to options for improving the efficiency of light-duty vehicles in the past decade. Consequently, a number of very promising approaches have been identified and well-documented (see, for example, Bleviss, 1988; Goldemberg et al., 1988, for more extensive discussions of the technical options for improving fuel efficiency of light-duty vehicles). These efficiency improvements must be considered in the context of several other societal and consumer concerns related to light vehicles, such as urban air quality, safety, comfort, and performance. These other goals also affect the patterns of vehicle technology development.

Fuel-Efficiency Improvements. A number of techniques for improving the fuel efficiency of vehicles that use traditional petroleum-based fuels (i.e., gasoline and diesel fuel) are currently available. Although average fuel efficiency for new cars in the industrialized countries is between 25 and 33 mpg (7.7-10 litre/100 km) (IEA, 1987), several vehicles that are roughly twice as efficient are commercially available: the Ford Escort diesel, the Honda City and Civic, and the Chevrolet Sprint all average greater than 50 miles per gallon (5 liters/100 km). As indicated in Table 7-2, there are larger prototype vehicles currently being tested that are substantially more efficient. In addition, a great deal of research on improving fuel efficiency is being conducted by the automobile industry. Improvements are possible in several areas as outlined in Box 7-1.

Box 7-1 provides only a few examples of the many improvements already possible with current technology. Research is proceeding rapidly and will undoubtedly yield further opportunities for improved fuel efficiency in the next decade. It is clear that opportunities exist for major reductions in light-duty fuel use by the end of this century. This is particularly true for the United States, which is still lagging behind most other industrialized countries in the average fuel efficiency of new cars sold (see Table 7-3), partly due to the preference for larger cars in the U.S.

TABLE 7-2

High Fuel Economy Prototype Vehicles

Company	General Motors	British Leyland	Volkswagen	Volkswagen	Volvo	Renault	Renault	Peugeot	Peugeot	Ford	Toyota
Model	TPC (Gasoline)	ECV-3 (Diesel)	Auto 2000 (Diesel)	VW-E80 (Diesel)	LCP2000 (Diesel)	EVE+ (Diesel)	VESTA2 (Gasoline)	VERA+ (Diesel)	ECO 2000 (Gasoline)	(Diesel)	AXV (Diesel)
Number of Passengers	2	4-5	4-5	4	2-4	4-5	2-4	4-5	4	4-5	4-5
Aerody-Namic Drag Coefficient	.31	.24-.25	.25	.35	.25-.28	.225	.186	.22	.21	.40	.26
Curb Weight (LB)	1040	1460	1716	1540	1555	1880	1047	1740	990	1875	1430-Target
Maximum Power (HP)	38	72	53	51	52,88	50	27	50	28	40	56
Fuel Economy (MPG)	61 City 74 Hwy	41 City 52 Hwy	63 City 71 Hwy	74 City 99 Hwy	63 City 81 Hwy	63 City 81 Hwy	78 City 107 Hwy	55 City 87 Hwy	70 City 77 Hwy	57 City 92 Hwy	89 City 110 Hwy

Source: Bleviss, 1988.

TABLE 7-3

Actual New Passenger Car Fuel Efficiency
(Gasoline consumption in liters per 100 kilometers)

								Projections/Targets		
	1973	1978	1979	1980	1982	1983	1984	1985	1990	2000
Australia	NA	11.8	11.2	10.1	9.8	9.5	9.5		8.5[1]	
Canada	NA	11.5	11.5	10.3	8.5	8.5	8.4	8.2	7.4	6.8[2]
Denmark	9.0[3]	NA	NA	8.6	NA	7.3	7.0	7.1		
Germany	10.3	9.6	9.4	9.0	8.3	8.0	7.7	7.5		
Italy[4]	8.4	8.3	8.3	8.1	8.3	8.0	NA	7.8	7.4	
Japan	10.4	8.8	8.6	8.3	7.7	7.8	7.8	7.8		
Netherlands	NA	9.2	8.9	8.8	8.5	NA		9.1	8.6	7.8
Sweden	NA	9.3	9.2	9.0	8.6	8.6	8.5	8.5		
United Kingdom	11.0	9.1	9.0	8.7	8.1	7.9	8.8	7.6		
United States	16.6	11.8	11.6	10.0	8.9	9.0	8.9	8.7	8.8	8.2

[1] 1987 target.
[2] 1995.
[3] 1975.
[4] The figures for Italy represent average efficiency of the total car fleet.

Source: IEA, 1987a

BOX 7-1. TECHNOLOGIES FOR AUTOMOTIVE FUEL EFFICIENCY

- Weight Reductions--Many of the most efficient cars substitute non-traditional materials for steel to achieve weight reductions, which contributes to their superior operating efficiency. Much greater weight reduction appears possible by substitution of high-strength steels, aluminum, plastics, ceramics, and composite materials (Bleviss, 1988).

- Aerodynamic and Drag Improvements--In 1979 the average "coefficient of drag" (C_D) for the U.S. was 0.48 and in Europe was 0.44. Currently, some production models such as the Ford Sable and Taurus, Subaru XT Coupe GL-10, and Peugeot 405 achieve a C_D of 0.3 or less. An experimental prototype, the Ford Probe V, has achieved a C_D of 0.137 (Bleviss, 1988). Incorporation of some of the design features currently in prototypes could reduce drag for production vehicles significantly over the next decade. Rolling resistance is being reduced with advanced radial tires. General Motors has recently introduced a "fourth generation" radial tire that reduces rolling resistance by 10-12% from the previous generation. An Austrian company has developed a more advanced tire concept, a liquid-injection-molded (LIM) polyurethane tire. Preliminary tests indicate improvements in rolling resistance as well as tread mileage (Bleviss, 1988).

- Engine and Drive Train Improvements--Several researchers have identified a number of improvements to conventional light vehicle propulsion systems and transmissions that could dramatically increase efficiency (see Bleviss, 1988; von Hippel and Levi 1983; Gray 1983; OTA 1982). One interesting example is the use of continuously variable transmissions (CVT), which eliminate some of the energy losses during shifting and allow the engine to be operated closer to full load at varying speeds. Another possible innovation is an engine-off feature with energy storage capability during idle and coast. In addition, advanced engine designs currently in prototype could be much more fuel efficient than current technology. One example is the adiabatic diesel engine shown in Box 7-2.

Despite the fact that improvements have been identified, it is not clear whether, and at what rate, new technology will be incorporated into automobile designs. Clearly, opportunities for dramatic efficiency improvements exist, but costs associated with these opportunities must be considered. The U.S. Office of Technology Assessment conducted a detailed analysis of the potential for and cost of future automobile fuel efficiency improvements. The study included considerable interaction with automobile manufacturers and other experts on fuel efficiency measures, and concluded that it was technically feasible to achieve average new car fuel efficiency levels in the range of 3.4-4.7 liters/100 km (50-70 miles per gallon) by 2000. It also found that "The consumer costs of fuel efficiency range from values that are easily competitive with today's gasoline prices to values that are considerably higher." (OTA, 1982, p.14).

OTA found that the cost of efficiency improvements varied greatly depending on the actual performance of potential design changes, the success of developing production techniques that can hold down the variable cost increases, and the value consumers place on future fuel savings. With optimistic assumptions, OTA estimated the cost of fuel efficiency measures to be as low as $60-$130/car during the 1985-2000 time period. With alternative assumptions, the cost of efficiency improvements could be as high as $800-$2,300/car.

Von Hippel and Levi (1983) conducted a computer analysis of the cost of introducing a number of specific measures that would improve fuel efficiency, beginning with the 1981 Volkswagen Rabbit diesel. A package of specific improvements that would improve the fuel economy from 5.2 to 3.3 l/100 km (45 to 71 mpg) was estimated to cost about $500 per car.

Goldemberg et al. (1988) and Bleviss (1988) however, suggest that cost estimates toward the lower end of the OTA range are more likely for several reasons. First, a number of other benefits to the consumer would result from some of the efficiency improvements. Alternative materials, for example, also may reduce maintenance costs. There is also some evidence that, contrary to popular expectations, use of more plastics and plastic composites may in some cases increase passenger safety (Bleviss, 1988). The inclusion of the engine-off feature may prolong engine life. If the value of these other benefits is deducted from the cost of fuel-efficiency improvements, more rapid improvements may be cost-effective.

A second reason for lower cost estimates is that the cost of individual improvements may not be additive. Some costs may be offset by the savings from combining measures and integrating a number of related changes into ongoing production process changes. Vehicle manufacturers periodically make major investments in design changes, incorporating style concerns as well as engineering improvements. Chrysler recently conducted a study comparing the costs of producing a conventional steel vehicle and an alternative made principally of composite plastics. Although the composite material is more costly, its use allows a dramatic reduction in the number of parts and hence, assembly costs. The study concluded that the number of parts might be reduced by as much as 75%, and that the overall production costs for the composite vehicle would be only 40% of those for the corresponding steel vehicle (*Automotive News*, 1986).

On the other hand, automobile manufacturers have recently expressed the view that further fuel efficiency improvements may be more difficult and costly to achieve than estimates from the early 1980s suggest (Plotkin, 1989). Concerns raised by the manufacturers include the following:

- most of the cost-effective efficiency measures that are acceptable to consumers have been implemented in the last decade;
- performance of actual production models incorporating design changes for efficiency have fallen short of engineering calculations;
- there are major technical uncertainties and marketability problems associated with many of the fuel efficiency technologies (e.g., advanced diesels, two-stroke engines)
- real trade-offs do exist between further fuel efficiency improvements and environmental (particularly for NO_x emissions) and safety standards.

Alternative Fuels. A number of alternative fuels have been proposed for light-duty vehicles in the past few years. In the U.S. these proposals have been driven primarily by concerns about the effects of emissions on urban air quality and the impact of petroleum-based fuels on energy security. Only recently have analysts focused attention on the greenhouse contributions of alternative fuels. Near-term options of interest include the use of alcohols--both ethanol and methanol, as blends with traditional fuels or as complete substitutes--and direct use of compressed natural gas. The discussion below refers to dedicated alternative-fueled vehicles designed and optimized for the alternative fuel. In the near term, however, "flexible fuel" vehicles may be produced that would be capable of burning one or more of the alternative fuels as well as gasoline. In this case, because vehicles are not optimized, energy efficiency may be less than optimal (and greenhouse gas emissions would be higher).

Methanol, as well as ethanol, can be produced from biomass. If these resources are replaced as they are used, then their combustion should not contribute to the global warming problem in the long run. In the U.S. and globally, however, natural gas would be the most likely feedstock for methanol in the near term. The estimated net contribution to greenhouse gases when gas is used as a feedstock will be roughly equivalent to that from burning gasoline from petroleum. On the other hand, greenhouse gas emissions from the use of coal-based methanol, measured over the entire fuel cycle, are about double those from crude oil-derived gasoline (DeLuchi et al., 1987). A shift from natural gas to coal in the long run could lead to large increases in greenhouse gas emissions.

Compressed natural gas (CNG) as a transport fuel produces fewer CO_2 emissions per unit of energy released than any other fossil fuel, and also seems to be among the cleanest fuels available when considering its emissions of other gases that affect urban air quality (e.g., NO_x, CO, and VOCs, although some questions remain about the level of NO_x emissions from CNG vehicles). However, leaks of natural gas, primarily methane (CH_4), from the production, distribution, and refueling processes, could add to the concentrations of this greenhouse gas. Some researchers estimate that this increase in methane could offset the advantage of lower CO_2 emissions. The degree to which methane releases would increase or could be controlled is highly uncertain.

CNG is currently used as a transport fuel in Canada and New Zealand, among other industrialized countries. In New Zealand, CNG, LPG, and synthetic gasoline (from natural gas) meet half of the total gasoline demand. Other industrialized countries have small alternative fuels programs, mainly based on CNG, LPG, and methanol (Sathaye et al., 1988).

Ethanol is likely to be produced from biomass but is also likely to have difficulty competing economically unless its production is heavily subsidized by government. Additionally, ethanol production by means of current technologies relies on biomass feedstocks such as corn and sugarcane, which are also food crops. This competition with food production raises concerns about the long-run viability of this approach.

In summary, in the near term it appears that the technical potential for industrialized countries to achieve reductions in greenhouse gas emissions from the use of alternative fuels is limited. The CO_2 reductions from alternative fuels in industrialized countries would not be enough to offset projected growth in vehicle miles traveled. However, their use in combination with fuel efficiency improvements may help alleviate other concerns related to urban air quality and energy security without increasing the global warming commitment. As discussed later, in the longer term, alternative fuels derived from renewable sources may play a key role in reducing greenhouse gas emissions in the transportation sector.

Tradeoffs With Other Goals. The governments of many industrialized countries regulate light-duty vehicles to reduce emissions of a number of air pollutants. In addition, consumers value performance attributes other than fuel efficiency, as well as comfort, safety, and cost in their choice of automobiles. To the extent that proposed fuel-efficiency improvements or alternative fuels involve tradeoffs against these other goals, or are perceived to require such sacrifices, they may be more difficult to implement.

Safety is a major concern long associated with light-duty vehicles. Some industrialized countries regulate the manufacture, sale, and maintenance of vehicles to improve safety. In the 1970s and 1980s, U.S. safety standards significantly improved vehicle safety. Some evidence exists of a correlation between size and weight reductions and increases in injury and fatality for currently available vehicles (OTA, 1982). Clearly, effects on safety must be considered in the evaluation of technical alternatives for improving fuel efficiency.

Weight reductions to improve efficiency may in fact reduce the structural strength of vehicles, thus making them less safe; however, it is not true that the use of lighter materials always reduces safety. U.S. government crash tests on the Nova, for example, have consistently shown the car's crash performance to be superior to other vehicles weighing as much as 50% more (Bleviss, 1988). In addition, options for improving automobile safety, such as air bags, automatic seat belts, as well as fundamental design changes, could improve both efficiency and safety if pursued as a national goal by regulatory bodies and manufacturers.

Another major concern associated with automobiles is their emissions. Vehicles emit several pollutants--particulate, volatile organic compounds (VOCs), carbon monoxide (CO), and nitrogen oxides (NO_x)--which contribute to urban air quality problems and indirectly to climate change. Some options for increasing fuel efficiency (and thus reducing greenhouse gas emissions) have the potential to worsen local air pollution problems. For example, diesel engines are more fuel efficient than gasoline-powered automobiles, but diesel engines tend to produce much greater emissions of particulates (many of which are cancer-causing compounds) per mile travelled.

Another complicating factor is related to the way in which vehicle emissions standards are defined. In most industrialized countries pollutant emission requirements for vehicles are applied on a grams-per-mile (or kilometer) basis. One concern about this approach is that it may not encourage development of technologies that would simultaneously improve fuel efficiency and reduce emissions of urban air pollutants, even though such technological options exist (Bleviss, 1988). In addition, as fuel efficiency improves, the marginal cost of driving would decline, assuming fuel prices remain constant, which might induce vehicle operators to drive more than they otherwise would. If this effect is significant (an unresolved empirical question), it would offset some of the expected reductions in greenhouse gas emissions and could also result in a net increase in emissions of conventional urban air pollutants.

Conversely, some of the options for reducing emissions of pollutants can lead to increases in emissions of greenhouse gases. As noted above, switching to methanol fuels could increase greenhouse gas emissions if the methanol is derived from coal. Similarly, use of electric cars could result in large net increases in greenhouse gas emissions if the electricity were generated from fossil fuels.

There are potential solutions to all of the problems illustrated. For example, new diesel cars are much cleaner than earlier models. Mercedes Benz and Volkswagen have now developed emission control devices that make it possible for their diesel cars to meet the strict California particulate standard of 0.2 grams/mile (Bleviss, 1988). In addition, emission standards could be modified (e.g., to grams per gallon in conjunction with higher efficiency standards, or direct regulation of CO_2 emissions) to encourage fuel-efficiency improvements that would also benefit local air quality. Over the long term, it is important that options like methanol-fueled and electric vehicles are promoted in conjunction with non-fossil (or at least non-coal) energy inputs.

Many consumers are concerned about sacrificing size, comfort, or driving performance to achieve major improvements in fuel economy. For several years, however, analysts have demonstrated possible design changes that would reduce fuel consumption while retaining the size and performance of a large automobile (e.g., Forster, 1983).

Some of the prototype high-efficiency vehicles have already demonstrated that size and acceleration do not necessarily have to be sacrificed. The Volvo LCP 2000, with an average fuel efficiency of 3.9 l/100 km (65 mpg), accelerates from 0 to 60 miles per hour in 11 seconds--compared with 13.1 seconds for the average acceleration of the U.S. new-car fleet (1986 models, which averaged only 8.4 l/100 km, or 28 miles per gallon). Likewise, a recently developed Toyota lightweight prototype car is designed to seat 5-6 passengers while achieving 2.9 l/100 km (80 mpg) under urban driving conditions (Bleviss, 1988).

In summary, it appears technologically quite feasible to achieve, for example, a new-car average fuel efficiency of 4.7 l/100 km (50 mpg) in the U.S. by 2000, while maintaining or improving current standards of safety, air pollutant emissions, comfort, and engine performance. This would imply, through vehicle turnover and continuing technical innovation, that fleet average efficiency would reach about 4.7 l/100 km (50 mpg) by 2010. This achievement would require, however, a strong commitment by government and industry. The reductions in energy (and greenhouse gas emissions) from this improvement would be significant.

The U.S. Department of Energy (U.S. DOE, 1987c) has recently projected that automobile vehicle miles travelled (VMT) in the U.S. will increase over 50% by the year 2010 (from 1,315 to

2,032 billion miles). In calculating future transportation energy use, the report also projects that automobiles will average about 8.7 l/100 km (27 mpg) in 2010 (overall average of all operating vehicles, not new-car average). If automobiles averaged 4.7 l/100 km (50 mpg), the energy consumed would be reduced by over 45%, or more than 30 billion gallons of gasoline (3.8 EJ[1]) in 2010--more than a 40% decline from the 1985 consumption level (as opposed to the 7% increase projected by DOE). To achieve these results, it would be necessary for automobiles to perform at the specified fuel efficiency over the life of the vehicle. Currently, there is considerable degradation in fuel efficiency over the life of an automobile. This requires further study and could limit the expected energy savings from fuel economy programs. In addition, the current trend in the U.S. toward light-duty trucks as personal transportation vehicles could offset some of the efficiency gains if it continues in the future. Efficiency improvements in light-duty trucks and/or programs to discourage personal use of these vehicles could produce significant energy savings in the U.S. (The VMT and average mpg assumptions in the DOE analysis are higher than in the No Response scenarios used in this report, but illustrate the potential for improvement). Decreasing fuel use in the U.S. could also support many important national goals such as reducing international trade deficits and improving energy security. Improvements of this magnitude could be made for the OECD as a whole and would undoubtedly also spill over to the non-OECD countries that produce vehicles for sale in the OECD and/or import vehicles or technology from the OECD. Most light-duty vehicles currently in production are derived from designs that originated in the OECD (Bleviss, 1988).

Freight Transport Vehicles

Diesel trucks use about 14% of the oil consumed for transportation in OECD countries (von Hippel and Levi, 1983). Improvements in efficiency in this sector could, therefore, have a noticeable effect on total energy use. Current prototype vehicles could reduce energy use per ton mile in the U.S. by as much as 40% for truck transport (*Automotive News*, 1983). Goldemberg et al. (1988) have estimated that further improvements on the order of 50% or better could be achieved with existing technology and at reasonable cost. Box 7-2 describes one of the most promising advanced diesel technologies. OECD truck fuel use for 1985 totaled about 5.3 EJ. A 50% improvement in fuel efficiency over the next several decades seems feasible if aggressively pursued. As truck freight ton miles are projected to grow in the future, this level of improvement could save at least 2.6 EJ by 2010.

---

[1] EJ = exajoule; 1 exajoule = 10^{18} joules

Both rail and water transport are much more efficient than trucks on a ton-mile basis. To the extent that shippers could be encouraged to shift freight to these modes in the future, either through price incentives or other policy mechanisms, net energy use for freight transport could be reduced. One interesting approach is being testing by General Motors Corporation (GM). GM has developed a new truck trailer that can also be easily converted to a rail car and connected to a freight engine. This would allow loading of truck trailers at source points, truck hauling to the nearest rail terminal, and conversion to rail without unloading/reloading. Likewise, near the destination, the transition back to truck is simple. GM has estimated that for hauls of over 200 miles, this approach could reduce energy use to 20% of current energy use for an all-truck haul or 50% of a conventional rail shipment (Sobey, 1988).

Improvements in ship fuel efficiency are also possible. Using some of the same diesel engine technologies identified for truck engines, 30-40% improvements in efficiency may be possible over the next several decades. Wind-aided cargo ships may also improve efficiency somewhat in the future.

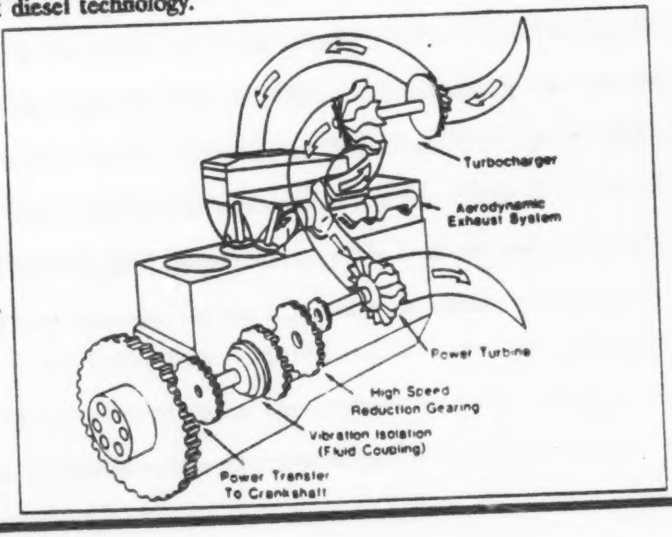
BOX 7-2. ADIABATIC DIESEL ENGINE TECHNOLOGY

The diesel engine is currently the most efficient power plant used in heavy duty and some light duty vehicles. Little has changed in its basic design over the years. However, motivated by the energy crises of the 1970s, engine designers began trying to improve the fuel-efficiency of diesels even further. One of the most promising results of this research is the adiabatic engine, which combines new structural ceramic materials and turbocharging to increase the effective use of the heat generated during combustion.

- Adiabatic design, which means "without heat loss," increases efficiency by retaining heat in the combustion chamber instead of losing it to exhaust gases and the engine coolant, harnesses the high pressure exhaust gases, and reduces weight and parasitic power losses by eliminating the normal cooling system.

- As shown in the figure below, turbocompounding increases the pressure of gases in the combustion chamber using a turbocharger and then harnesses the extra pressure of the exhaust gases with a turbine connected to the engine crankshaft. Structural ceramics, which are being developed to withstand temperatures and pressures reaching 1000°C and 2000 psi, respectively, will be used to insulate the combustion chamber, allowing greater thermal efficiency.

- Cummins Engines and Adiabatics in the U.S., as well as Japanese automakers, are at the forefront of introducing the adiabatic engine both for heavy duty trucks and passenger vehicles. A Ford Tempo with an adiabatic engine is projected to be able to have a fuel economy of 80 mpg. Along with the consequent reduction in CO_2, additional improvements are expected in hydrocarbon, CO, and NO_x emissions, and particulates are expected to be reduced by as much as 60-80% over current diesel technology.


Turbocharger
Aerodynamic Exhaust System
Power Turbine
High Speed Reduction Gearing
Vibration Isolation (Fluid Coupling)
Power Transfer To Crankshaft

Source:
Kamo, 1987.

Aircraft

Dramatic improvements in fuel efficiency have been achieved in the airline industry over the past decades. From 1970 to 1980 fuel use per passenger mile in the U.S. declined by over 40% (Holcomb et al., 1987). Nevertheless, by 1980 energy still accounted for about 30% of total operating costs for commercial airlines in the U.S. (Goldemberg et al., 1988). Since 1980, energy intensity has continued to decline due to some additions of more efficient aircraft and continued improvements in load factors (revenue passenger miles divided by available seat miles - U.S. DOT, 1988), but at a slower rate (from 1980 to 1984 the improvement was about 4% - Holcomb et al., 1987). The decline in the rate of efficiency improvement is highly correlated with declining energy costs. For example, between 1980 and 1987, nominal fuel prices declined by nearly 40% (U.S. DOE, 1988b), reflecting a drop of more than 50% in real terms. Combined with some efficiency improvements, this has resulted in energy costs being reduced to a much smaller percentage, 10-15%, of total operating costs. Thus, the economic incentive to reduce energy intensity has been greatly reduced.

Because of the historical importance of fuel costs, however, a great deal of research has been conducted and within the industry to identify opportunities for improvements in efficiency. Currently, commercially-available new planes are more than 25% more efficient than the 1980 fleet average (Smith, 1981 for 1980 average, Ropelowski, 1982 for test results of new 757 and 767 models). Already improvements have been identified which, if incorporated into aircraft design, could reduce fuel use per passenger mile to less than one-third of the current average (Maglieri and Dollyhigh, 1982; Smith, 1988). It may be technically possible to reduce fuel use per passenger mile to 50% of the current average by the year 2010.

The rate at which airline passenger miles will increase in the future is, however, a matter of considerable uncertainty. Some industry sources are projecting very high rates of growth in the next few decades, which could offset the projected gain due to improvements in energy per passenger mile. Kavanaugh (1988), for example, projects increases in global jet fuel use of 60 to 120 percent by the year 2025 despite assuming significant substitution of more fuel-efficient aircraft during the same period.

Control of NO_x and CO Emissions from Mobile Sources

The United States and most other OECD countries currently regulate the emission of hydrocarbons (HC), carbon monoxide (CO), nitrogen oxide (NO_x), and particulate matter (PM) on a gram per kilometer basis. Many developing countries have recently adopted some emission control standards as well. The standards vary for the weight class of the vehicle as well as by the type of engine.

International comparisons of emissions standards are difficult because test procedures vary, but it is generally recognized that U.S. standards are among the most stringent in the world. For light-duty gasoline vehicles (which constitute a majority of the U.S. fleet), the U.S. standards are 2.1, 0.25, 0.62 g/km for CO, HC, and NO_x, respectively. Emission standards in most European countries are significantly less stringent than in the U.S. (OECD, 1988). Many developing countries have much less stringent standards, or none at all.

Vehicles sold in the United States control emissions in two steps. The first step is to control the amount of pollutants formed during the combustion process. During combustion, the prime determinant of the amount of carbon monoxide formed is the air/fuel mixture. As the air/fuel ratio increases, CO emissions fall. On the other hand, NO_x emissions increase as the air/fuel ratio rises, a result of the concurrent increase in combustion temperatures, the primary determinant of NO_x formation. Higher combustion temperatures are often associated with increased power. An engine designed for greater power will generally produce higher "engine-out" NO_x emissions than a engine designed for fuel economy. Electronic engine management systems have, however, been able to minimize these tradeoffs, since many of the critical engine parameters (like the air/fuel ratio) can be controlled much more precisely (NAPAP, 1988; OECD, 1988).

The second step is to treat the "engine-out" exhaust after combustion to reduce emissions to the acceptable standard. To control the "engine out" emissions, both catalysts and exhaust gas recirculation (EGR) are used on virtually all new U.S. (and Japanese) passenger cars, usually in conjunction with electronic engine management systems. Since 1981, the primary catalyst system used on U.S.-bound cars has been the three-way converter--named for its ability to reduce emissions of HC, NO_x, and CO, as opposed to just one or two of the gases. Some cars also use a second oxidation catalyst to catch additional HC and CO. Catalysts use a variety of precious metals, including platinum, rhodium, and palladium, to breakdown or reduce the unwanted emissions without causing the metals themselves to react (*Automotive News*, 1988; OECD, 1988; White, 1982). Exhaust gas recirculation reduces NO_x emissions by reinjecting a portion of the inert exhaust into the engine's incoming air. The inert exhaust gas cannot react in the combustion process and reduces peak temperatures during combustion. As a result, less NO_x is formed. Today, all U.S. light-duty vehicles have EGR systems (Husselbee, 1984).

Some tightening of existing U.S. standards has been considered and determined to be technically feasible, although expensive (NAPAP, 1988). More significant improvements in global emissions of NO_x and CO would result from the extension of U.S. standards to the rest of the OECD and ultimately, to the rest of the world. These extensions are assumed over time in the Stabilizing Policy scenarios.

Current technologies for compliance with U.S. emissions standards have added substantially to the cost of new vehicles, although improving technology may reduce the incremental cost in the future (U.S. EPA, 1985, NAPAP, 1987). Also, with existing technologies a modest tradeoff has been documented between emissions control, and fuel efficiency and performance, at the current level of U.S. emissions standards (White, 1982, OECD, 1988). Tradeoffs and cost for tighter standards, however, would depend on the stringency of the standards and the level of technology, as well as the demand for other characteristics like performance.

Near-Term Technical Options: Developing Countries

Transportation energy use is a serious concern in developing countries for several reasons. Worldwide, energy used for transportation is almost exclusively oil. From 1973 to 1986 oil use by developing countries increased by 60%. During this same period, oil use by OECD countries declined by 13%. Recent projections by the Department of Energy (U.S. DOE, 1987c) indicate that the overwhelming majority (86%) of growth in oil consumption in the "free world" (defined by DOE to exclude the centrally-planned economies of Eastern Europe, the Soviet Union, China, Cuba, Kampuchea, North Korea, Laos, Mongolia, and Vietnam) through the year 2010 could come from developing countries. The largest component of the dramatic increases in oil use in developing countries during the last decade is in the transportation sector. For 15 of the largest developing countries, about 50% of the growth in oil consumption in the 1970-1984 period has been in transportation applications (Meyers, 1988). Thus, indications are that energy use for transportation has been growing at a very rapid rate in recent years in developing countries, and this high rate of growth is projected to continue in the future.

Although some developing countries have been successful in implementing programs to reduce fossil-fuel use (or at least oil use) in other sectors, very little attention has been paid to the transportation sector, either by these countries themselves or by international development assistance agencies (with a few notable exceptions, e.g., Brazil and, more recently, several other countries, including the Philippines). There are a number of reasons why it is difficult for developing countries to implement the technical options that have been relatively effective to date in the industrialized countries.

First, information about transportation energy use is limited in many developing countries. It is very difficult to estimate, for example, what portion of the fuel is used in new versus old vehicles, light trucks versus heavy trucks, two- and three-wheeled vehicles, etc. The information that is available, however, suggests other problems.

Road vehicles tend to be kept in service far longer in developing countries and often are used for purposes other than what they were originally designed for. There is some evidence that aging vehicles are often poorly maintained in developing countries. Poor roads also often contribute to increased energy use per vehicle kilometer of travel (VKT). Urban congestion can also have this effect, although in some cases it may also act as a deterrent to increases in VKT. Although heavily utilized, mass-transit systems in developing countries are generally poorly developed and are also affected by poor or congested road systems.

Thus, the approaches that have been successful in slowing the growth of transportation energy use in the industrialized countries over the past 15 years may not be as effective in many developing countries. Industrialized countries have been able to significantly reduce the average consumption of fuel per highway mile by replacing existing vehicles with more efficient newer models and developing or expanding mass transit in urban areas. The effectiveness of both strategies in most developing countries is much more limited because of the slower turnover of vehicles and lack of capital to invest in infrastructure improvements.

On the other hand, it is expected that as developing countries reach a certain per capita income, they will experience a rapid explosion in the demand for personal vehicles that will dramatically increase transportation energy use (Sathaye et al., 1988). The fuel efficiency of new vehicles available during that period can have a significant effect on future transportation energy use.

Those developing countries that do not have domestic oil resources are concerned that increasing their imports of oil will diminish the already-limited foreign exchange available to finance development and hence, limit long-term growth. Thus, there is great interest emerging in limiting oil use for transportation. Efficiency improvements, though often more difficult to achieve than in industrialized countries, clearly are part of the solution. Biomass-based alternative fuels are very important for some developing countries (Brazil, for example) in the near term. Other developing countries (like some industrialized countries) may have natural gas that can be used for transportation or other types of biomass-based options. Generally, the transportation energy solutions that would be attractive to developing countries for the purpose of reducing oil imports - efficiency improvements and alternative fuels - are also beneficial in reducing greenhouse gas emissions. One exception is the use of coal as a rail fuel, which occurs in China and India and results in both lower energy efficiency in rail transport and in more CO_2 per unit of fuel consumed. However, this option may appear attractive to countries concerned primarily with minimizing oil imports.

Fuel-Efficiency Improvements

As individual developing countries reach a certain level of economic activity and per capita income, it is expected that the demand for personal vehicles will "take off," as occurred historically in several more-industrialized countries. Currently, gasoline prices are higher in many developing countries and oil imports frequently make up a large fraction of total imports in developing countries.

Therefore, improvements in the efficiency of new vehicles, both light- and heavy-duty, should be very attractive in developing countries to reduce fuel costs.

Improving Existing Vehicles

Because of capital scarcity, all types of vehicles are kept in service far longer than they are in industrialized countries. Certainly for some developing countries, programs to improve the quality of maintenance or accelerate retirement of older vehicles may be very useful in reducing oil consumption (and greenhouse gas emissions).

For the same reason that aging vehicles are kept in service, new classes of intermediate vehicles, often used as low-cost transport vehicles, have emerged in developing countries. These are generally produced locally, often by small companies or even a single individual. Some alternative vehicles, notably the Chinese tractor converted for passenger transport, are adaptations of vehicles designed for other purposes. India also does a significant amount of road transport in rural areas with tractors. As a means of passenger or freight transport, many of these vehicles are very energy-inefficient. The Chinese tractors, for example, are estimated to use 75% more fuel than would a four-ton truck while carrying only one ton; these tractors account for 27% of the total diesel fuel use in China (World Bank, 1985). Programs to improve the efficiency of these vehicles or to replace them with more efficient alternatives may be very effective in the near term in some developing countries.

Alleviating Congestion and Improving Roads

In rural areas of many developing countries, roads are so poor that traffic must move much more slowly than is customary for intercity travel in industrialized countries. Frequent stops and starts are also a problem in these areas. These conditions inevitably lead to reduced energy efficiency regardless of the quality of the vehicles themselves. A recent study has concluded, however, that poor road conditions do not appear to act as a deterrent to increased vehicle ownership in rural areas of developing countries (Meyers, 1988). Thus, carefully planned highway improvements could result in net reductions in fuel use in some countries. In addition to reducing fuel use in the existing mix of vehicles, better roads may allow "upsizing" of some of the existing traffic to larger trucks and buses that are much more efficient on a passenger- or ton-km basis. Encouraging the use of more efficient modes, such as rail transport, may also be possible in some cases.

In urban areas, congestion is already clearly a major problem in many developing countries (as it is in many industrialized countries) and is likely to become more severe as rapid urbanization continues in many developing countries. Although congestion, as already mentioned, reduces efficiency in fuel use, it may also act as a deterrent to increased vehicle use, promoting the widespread use of more efficient alternatives to personal automobiles, such as motorcycles and mass transit. The degree to which congestion functions as a deterrent to increased transportation energy use is uncertain and needs further investigation.

Thus, it is important to carefully evaluate local conditions in designing improvements to urban road systems, including more extensive roads but also better road maintenance and better planned roads. It may also be important to combine road improvements with other measures such as mass transit to achieve overall improvements in energy efficiency.

Alternative Modes of Transportation

In addition to encouraging expansion of urban mass transit, developing countries may wish to promote alternatives to highway transport in both rural and inter-city travel. Because major investments may be required to develop or improve highways for these types of travel, it may be more economically attractive to direct this investment into improved rail systems, for example, which move passengers and freight more efficiently. If highway improvement programs are carried out, however, they may be combined with the introduction of efficient bus systems, which would offer an attractive alternative to personal vehicle ownership and use.

Alternative Fuels

Alternative fuels based on locally-available resources may be economically viable and important options in developing countries much sooner than is the case for industrialized countries. In countries like Brazil, which have abundant agricultural land, commercial technologies to convert crops, such as sugarcane or corn, to produce ethanol may make sense (see **PART TWO: ENERGY SUPPLY**, for more detailed discussion of the Brazilian ethanol program). A fuels program based on sustainable biomass production is extremely beneficial in reducing net CO_2 emissions. Most developing countries would have difficulty, however, in diverting significant amounts of biomass, which is currently used for food, to energy purposes. Converting agricultural residues or forest products to fuel may make more sense if the conversion processes can be made economically attractive.

In other countries locally available natural gas may be readily converted to compressed natural gas (CNG), which would reduce emissions of CO_2 as well as many other air pollutants and also reduce oil imports. A recent review of international programs noted that most Asian countries and many Latin American countries that have domestic gas resources are conducting feasibility studies of CNG use and many have pilot programs in place (Sathaye et al., 1988). Where natural gas is currently vented or flared as a by-product of oil production, (e.g., in the Middle East), the availability of cheap local oil discourages investments in natural gas distribution and utilization systems.

A final fuel-switching option that could be helpful in the near term is replacing coal with diesel fuel or electricity in rail transportation systems. Coal use as a rail fuel has virtually disappeared in industrialized countries--primarily because coal-fired rail systems are markedly less efficient than the alternatives. In energy consumed per mile travelled, diesel trains are more than 3.5 times as efficient, and electrified rail is 13 times more efficient (compared on the basis of secondary energy consumed). If electricity is generated from coal, primary energy consumed and CO_2 emissions would be 3 times greater than the end-use energy consumed. Electric rail in this case would be about 4 times more efficient than coal-fired rail in primary energy consumption. However, a few developing countries with abundant coal resources and extensive rail systems--notably India and China--still use coal in rail transport. Although considerably less efficient, this option may be appealing from the perspective of minimizing oil imports. India has a program of gradual replacement underway, which is expected to eliminate coal use in rail systems by the year 2000. A shift to diesel fuel should reduce the CO_2 emissions from this source by a factor of five.

Near-Term Technical Options: Soviet Bloc Countries

In the USSR and Eastern Europe, transportation makes up a much smaller proportion of total energy use than is the case in industrialized countries--primarily because there are many fewer automobiles and trucks. However, that number is growing rapidly: from 1970 to 1980 the number of automobiles in the Soviet Union increased from 1.6 to 6.9 million (a rate of 15%/year), and the number of trucks rose from 3.2 to 5.1 million (4.7%/year).

On the other hand, fairly significant improvements have been made in recent decades in the efficiency of freight transport, primarily transport by rail. From 1960 to 1975, ton-kilometers of freight hauled by all forms of transport in the Soviet Union increased by 276%, while fuel use increased by 2.4% and electricity use increased by 418% (from a very small base). Overall, this represents a significant increase in energy efficiency due primarily to the replacement of coal locomotives by much more efficient diesel and electric engines (Hewett, 1984).

Given the rapid growth in the numbers of automobiles and trucks in the recent past, and in the number projected in the scenarios developed for this report, it appears that an important option for these countries will be to increase the efficiency of new highway vehicles. In addition, because of the large natural gas resources available in the Soviet Union (discussed in **PART TWO: ENERGY SUPPLY**), the feasibility of using compressed natural gas as a vehicle fuel may deserve further investigation.

Summary of Near-Term Technical Potential in the Transportation Sector

With aggressive programs to improve transportation energy efficiency across the board in industrialized countries, it appears that significant overall reductions could be made over time. Improvements in the efficiency of light-duty vehicles and freight transport could result in reductions of energy use on the order of 7 EJ of transportation energy from the No Response scenario levels by 2010 in the OECD. If the same efficient technologies were transferred to developing countries and the Soviet bloc, even larger reductions could be achieved below scenario levels because of the rapid expansion of vehicle stock in those areas. This suggests that the technical potential may exist to reduce energy use by 25 EJ by 2010. This estimate is higher than that assumed in the climate policy scenarios, where the maximum transportation energy reduction is about 32 E by the year 2025. Furthermore, it appears that there are fuel-switching options that could be implemented during this time period, which could reduce the greenhouse gases emitted per unit of energy consumed in transportation. The overall potential of these options has not been quantified.

Long-Term Potential in the Transportation Sector

Over the long term, technical possibilities for reducing greenhouse emissions from transportation greatly increase. The range of options runs from further improvements in highway vehicles and expanded use of alternative fuels, to alternative transportation modes, to measures that would reduce the need for transportation. All of these options are somewhat speculative and very sensitive to assumptions about the nature of society in the long term. The discussion here is intended to illustrate possible options rather than to suggest which choices should be made. Considerably more systematic and detailed analysis is required before useful comparisons can be made.

Urban Planning and Mass Transit

A major concern in many urban areas throughout the industrialized countries (and in many developing countries as well) is increasing traffic congestion. When vehicles spend an increasingly greater proportion of their time idling in stop-and-go traffic, they use more fuel and emit more air pollutants per mile travelled. In the near term, solutions to urban congestion problems are extremely difficult. For the long-term, however, alternative approaches to alleviating this problem will tend to incidentally benefit the climate warming problem. Mass transit systems not only reduce highway commuter traffic but the energy used per passenger mile is much lower. The energy intensity of one person commuting alone by car is over 4.5 MJ/km.[3] Average intensities (over all time periods) for bus and rail transit are reported to range from about 2.0-2.5 MJ/passenger-km (Holcomb et al., 1987). At normal commuting times transit systems tend to be much closer to fully-loaded, however, so that the energy intensities per passenger-mile would be even lower. The energy intensity of one person commuting alone by car is over 4.5 MJ/km (7,000 Btu/mile). Average intensities (over all time periods) for bus and rail transit are reported to range from about 2.0-2.5 MJ/passenger-km (Holcomb et al., 1987). At normal commuting times transit systems tend to be much closer to fully-loaded, however, so that the energy intensities per passenger-mile would be even lower. Similarly, efforts to encourage carpooling can relieve congestion and reduce fuel use at the same time.

---

[3] MJ = megajoule = 10^6 joules.

Another possibility is shifting to smaller, commuter vehicles. General Motors Corporation is testing a three-wheeled, one- or two- passenger, narrow commuter car, which is essentially more like a covered motorcycle than a traditional automobile. Because the vehicle is much narrower than a normal passenger car, a standard traffic lane could be split in half to double the carrying capacity of existing roads. Because the vehicle is small and aerodynamically-designed, it would also be much more fuel efficient than today's cars, achieving over 100 miles per gallon (Sobey, 1988). Clearly, some safety issues and other complexities in integrating such vehicles into current urban traffic patterns remain to be worked out.

The technical potential exists to design and construct urban areas that are much more energy efficient in terms of their transportation requirements (as well as in their energy requirements for other end uses). By comparing cities whose transportation energy use is very low, relative to global averages, with cities whose energy use in this sector is high, it is possible to identify differences in location patterns, mass transit systems, and other factors that can partially explain the differences in energy demands. In theory, it should be possible to introduce incentives that will cause the cities to developed similarly to the low energy examples over time. This may be especially important in developing countries where populations, especially urban populations, are growing rapidly.

Alternative Fuels

Use of **alcohol fuels** as an alternative to gasoline in highway vehicles is an option that is already receiving considerable interest for a number of reasons, as described earlier. Technologies currently exist for producing ethanol and methanol from various types of biomass. Further research, testing and commercial demonstrations could be helpful in improving performance and lowering cost. In the long run it appears that methanol may be preferable because the biomass feedstock does not necessarily have a food value and therefore is not in direct competition with food production.

Technologies currently exist for operating highway vehicles with **hydrogen fuel**. Such vehicles are not currently viewed as commercial, primarily because of the high cost of hydrogen fuel and difficulties in storing enough hydrogen on board for highway driving. A hydrogen-powered automobile built by Daimler-Benz of West Germany and a hydrogen-powered bus built by the Billings Energy Corporation of Provo, Utah, are examples of currently-operating test vehicles. These two vehicles use metal hydride storage tanks, one promising approach to the storage problem (Ogden and Williams, 1988). In addition, if the fuel-efficiency improvements described above are incorporated, future vehicles may be able to achieve driving ranges comparable to today's vehicles while carrying much less fuel on board. The possibilities for producing hydrogen at competitive costs are also improving with the development of solar photovoltaic technology (see **PART TWO: ENERGY SUPPLY**). Another attractive feature of hydrogen vehicles is that the engines and internal structure required are very similar to what CNG-powered vehicles would require. CNG is already being used in fleet applications in some countries and will be more widely-used in the future. This could provide a market for the initial transition to hydrogen when and if the cost and storage problems are resolved.

Electric-powered vehicles have been discussed for many years as an option for reducing oil use and/or urban pollution. As with hydrogen, the problem of storing enough energy on board to provide a reasonable driving range is an as-yet-unresolved obstacle. In addition, vehicle cost and performance ability comparable to the cost and performance of today's vehicles have not yet been realized. Concerns about higher future electricity costs could also retard penetration of electric cars, even if other problems were resolved.

The source of primary energy for both electric and hydrogen-powered vehicles will determine whether a switch to these fuels increases or decreases greenhouse gas emissions. Use of non-fossil sources of electricity, such as solar or nuclear, would decrease emissions of CO_2 and other greenhouse gases. Conversely, use of coal-fired generating capacity as the primary source of electricity or hydrogen would lead to increases in greenhouse gas emissions.

Expanded Use of Emerging Technologies

Telecommunications may substitute for many transportation services in the future. Teleconferencing is already replacing some types of business travel, although the magnitude of this substitution has not been quantified in energy terms as yet. In the future, as video conferencing equipment improves and is more widely available, this option could become more important, particularly if higher transportation costs and congestion act as incentives. Catalogue shopping, electronic mail, electronic advertising, and electronic banking are other applications of telecommunications that are beginning to replace specific transportation needs. A recent analysis projects that transportation energy use may decline in OECD countries because of these substitutions. As is the case with many energy efficiency improvements, the motivation for this substitution has very little to do with energy use. These substitutions are taking place because consumers and businesses perceive advantages in convenience, time saving, access to wider selections, and cost savings (Schipper, et al., 1989).

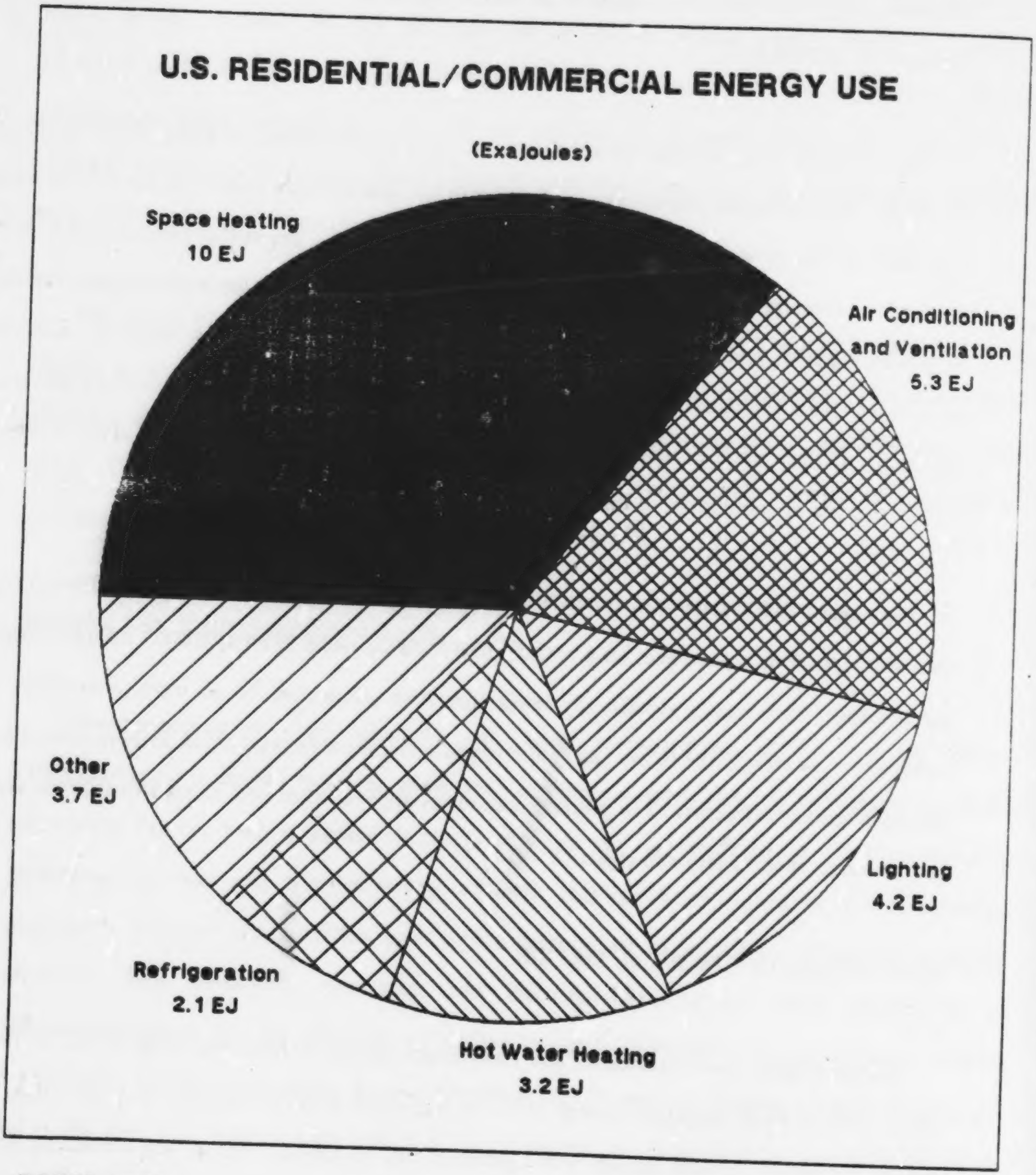
Fuel cell technology has many potential applications (described briefly in **PART TWO: ENERGY SUPPLY**). Two appealing characteristics of fuel cells are that cost-effectiveness is not fundamentally a function of size, as with many energy technologies, and that they are virtually pollution-free at the point of use (Jessup, 1988). Because of these characteristics, one possibility is to use small fuel cells to power highway vehicles. Input fuel can be derived from natural gas, coal,. or, ultimately, renewables-based hydrogen. Several different fuel-cell approaches are being researched and tested currently. If they prove economic, the fuel cell could provide very efficient and clean power for mobile sources at some point in the future.

High-speed rail systems are currently in commercial use in Japan and France. They compete well with aircraft or automobiles on a performance basis for some intercity travel. Energy consumed per passenger-kilometer is significantly lower than with automobile or air travel alternatives. As technologies develop in the future (e.g., superconductors), these systems could become more efficient and economically attractive. The primary constraints appears to be cost of constructing the systems and concerns about safety and rights of way.

RESIDENTIAL/COMMERCIAL SECTOR

In the United States residential and commercial energy services consumed 17 EJ in 1985, or about 29% of total secondary energy (36% of equivalent primary energy). For the OECD as a whole, the picture is quite similar, with residential and commercial energy use amounting to about 30% of the total secondary energy. Figure 7-7 shows the distribution of energy use within this category in the U.S. The largest component (more than a third) of residential/commercial energy

FIGURE 7-7



U.S DOE, 1987a.

use is for space heating; combined with air conditioning and ventilation, the overall use of energy for space conditioning accounts to more than half (54%) of all residential and commercial energy use. Lighting accounts for another 15%, hot water heating, 11%, refrigeration, 7%, and the remaining energy (13%) is divided among all of the other appliances and equipment used in residences and commercial establishments (U.S. DOE, 1987b).

As shown in Figure 7-8, global energy use in the residential and commercial sectors in the No Response scenarios grows by 29-65% by the year 2025. The relatively-wide range is apparent in all regions and reflects alternative assumptions about the rate of investment in buildings and in population growth. In addition, a shift toward electricity for a higher percentage of energy use in these sectors results in increases in end-use efficiency, but implies that primary energy required (accounting for losses in electricity generation) is growing more rapidly.

In the scenarios, the percentage of total energy used in the industrialized countries declines significantly over time. Residential/commercial energy use in 2025 for the OECD in the No Response scenarios ranges from slightly higher than today's levels to slightly lower. This reflects the slow rate of population growth and the technological advances that are already increasing energy efficiency in these countries.

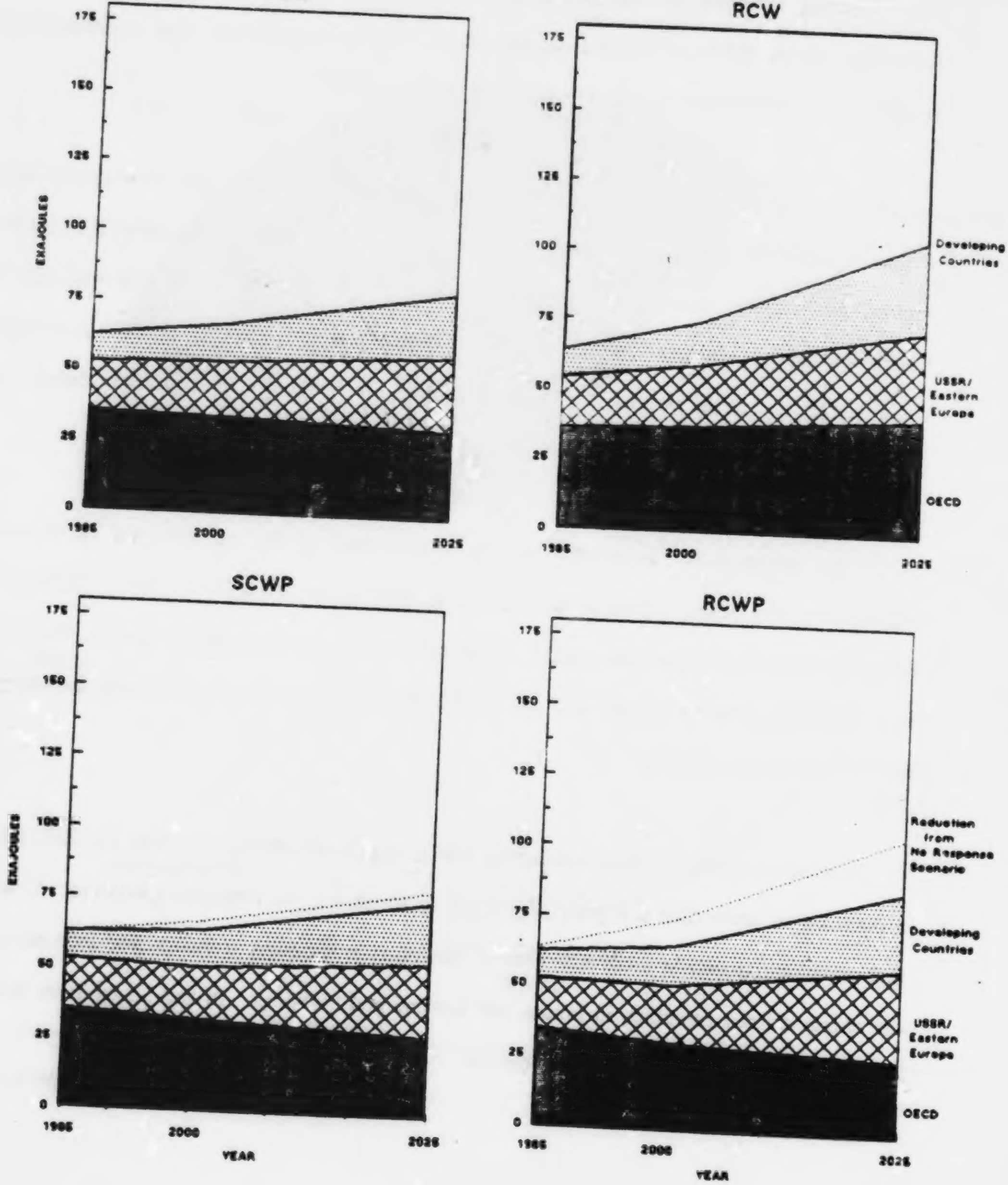
In contrast, residential and commercial energy use in developing countries for 2025 ranges from a doubling to more than a tripling of current levels in the No Response scenarios. It is expected that economic growth in these countries in the future will rapidly translate into increasing demands for energy-related amenities in homes and commercial buildings. In the Soviet Bloc increases are on the order of 50-75% for similar reasons.

best copy available

FIGURE 7-8

RESIDENTIAL/COMMERCIAL ENERGY USE BY REGION

(Exajoules)



Major technical improvements demonstrated in recent years offer the possibility that new residential and commercial buildings built in the future could require substantially less energy for heating and cooling. Because the stock of buildings turns over so slowly, it is also important to focus on retrofitting, which could reduce air conditioning and heating needs in existing buildings. Dramatic improvements in efficiency are also possible in lighting, particularly in commercial buildings, where lighting may account for a large share of the electrical energy used. Improvements in lighting efficiency also frequently have the added benefit of reducing the amount of waste heat produced by the lighting system and thus reducing the air conditioning requirements as well.

Options for reducing energy use in the residential and commercial sectors are fairly well characterized, at least in the OECD. As discussed below, potentials are very great, but due to the long turnover time of building stock, improvements may have to be phased in over a long time period. Figure 7-8 also indicates reductions of 5-16% in secondary energy use in these sectors by 2025 in the Stabilizing Policy cases. In addition, alternative fuels are introduced, particularly in developing countries, which further reduces the greenhouse impact of energy use. As discussed below, these reductions are small relative to the technical potential for improvements.

Near-Term Technical Options: Industrialized Countries

Improvements in Space Conditioning

Improved efficiency in space conditioning (heating and cooling) can be obtained in several ways. First, the design of new buildings can be altered to improve their insulating qualities, thus reducing losses in heating or cooling. Second, improved technologies can be applied to make existing buildings more weathertight, requiring less energy for heating and cooling. Finally, advanced technologies for heating and cooling equipment can be dramatically more efficient than devices currently in wide use.

A number of very thorough and high-quality reviews of the potential for energy efficiency improvements in buildings have been produced in recent years (see, for example, Hirst et al., 1986; Schipper et al., 1985). The discussion below draws on the extensive published literature to illustrate the technical potential for improvement.

New Residences. The potential for improving energy efficiency in new homes is very significant. Simply by **modifying the building shell to improve its insulating capabilities**, space heating energy requirements can be reduced dramatically. Current new homes in the U.S. require, on average, almost 40% less energy to achieve the same level of heating as the average existing house in the U.S. (See Box 7-3, which illustrates the range of energy requirements for space heating on a per unit of floor space basis). What is even more interesting is that the most efficient new houses built currently are 50% more efficient than the average new home. (It should be pointed out, however, that relatively few of these extremely-efficient homes are being built currently.) Very advanced prototypes and design calculations indicate that it is technically possible to build homes whose heating energy requirements would range from 15 to 20 kJ per square meter per degree day, or 10-12% of the average requirements for today's homes.[3]

In addition to the potential for improving the thermal properties of building shells, equally important advances have been made in developing **high-efficiency equipment** for both space heating and cooling. Already being marketed in the U.S. and in Europe are high-efficiency gas and oil furnaces that are about 95% efficient, compared with the average (about 75% efficient) for new furnaces in the U.S. (Geller 1988).

Substantial energy savings are possible in electrically-heated (and cooled) homes with recent efficient heat pump designs. The most efficient designs on today's market are about one-third more

---

[3] kJ = kilojoule, 1 kilojoule = 10^3 joules.

BOX 7-3 IMPROVING ENERGY EFFICIENCY IN SINGLE FAMILY HOMES

Space Heat Requirements in Single-Family Dwellings
(Kilojoules per square meter per degree day)

United States	
Average, housing stock	160
New (1980) construction in U.S.	100
Mean measured value for 97 houses in Minnesota's Energy Efficient Housing Demonstration Program	51
Mean measured value for 9 houses built in Eugene, Oregon	48
Calculated value for a Northern Energy Home, New York area	15
Sweden	
Average, housing stock	135
Homes built to conform to the 1975 Swedish Building Code	65
Mean measured value for 39 houses built in Skane, Sweden	36
House of Mats Wolgast, in Sweden	18
Calculated value for alternative versions of the prefabricated house sold by Faluhus	83
Version #1	83
Version #2	17

Source: Goldemberg, 1988.

The striking reduction, up to 90%, that is possible between the average home and new "low energy" homes, as illustrated by the figures above, is achieved through the use of state-of-the-art construction and design techniques and technologies; a few of the areas where significant changes have occurred include:

- Building Envelope - Larger wall and ceiling cavities, allowing for significantly more insulation, have been obtained with new construction materials and designs, such as "I-beam" framing members, raising R-values to as high as R-38 in some low-energy homes. Polyethylene vapor/air barriers in external walls reduce infiltration of outside air, one of the major sources of heat loss in most homes. Windows are being triple and even quadruple glazed, and, in some cases, incorporate low-emissivity films and inert gases, such as argon, between the panes to improve their insulating quality.

BOX 7-3 IMPROVING ENERGY EFFICIENCY IN SINGLE FAMILY HOMES (continued)

- Mechanical - These include heating, cooling, and ventilating systems. In addition to high efficiency furnaces, heat pumps and air conditioners, many low-energy homes incorporate air-to-air heat exchangers. These are needed to bring fresh air into the house, since natural infiltration is significantly reduced, but they improve energy efficiency by extracting approximately half the heat from the exhaust air and transferring it to incoming air. The newest development in mechanical ventilation is the heat pump exhaust system, which uses warm exhaust air to provide water heating.
- Active/Passive Solar Design, Thermal Storage - Many different designs have been developed to make better use of solar gain to provide heat. These include use of south-facing windows, greenhouses, atriums, etc., and are often combined with thermal storage systems that store heat collected during peak daylight hours for redistribution when it is needed at other times. Storage systems can also work in the reverse way, collecting cool air during the night and circulating it during warmer hours.

efficient than average. Advanced designs (such as ground-coupled heat pumps) not yet commercially available may provide even more efficient options over the next decade.

With super-insulated shells it may not be necessary to install a central heating system at all. Some of the advanced designs require so little heat input that small electric resistance heaters may be cost-effective in moderate climate areas. The greatly-reduced capital cost for this option may offset the increased cost for the super-insulating features. In very cold regions, the added cost of very efficient gas or oil furnaces would be justified. In regions where cooling is also required, the advanced heat pumps would probably be the most economic choice.

If all options were used in combination, it appears technically quite feasible for advanced building shells and efficient heating and cooling equipment to reduce space conditioning energy requirements in new homes to less than 10 percent of current average use.

Existing Residences. It is expected that the net growth in housing stock will be slow in the future in industrialized countries because of the extensive existing stock and low population growth. In addition, existing housing stocks have very long lifetimes. Therefore, existing stocks will dominate the residential sector for many decades. Thus, it is extremely important to focus on opportunities for reducing energy requirements in existing buildings. Many of the advances that have made possible the enormous potential energy savings for new homes are to some extent applicable to existing homes.

In general, retrofit improvements are less effective and more costly than those incorporated in the initial design of a new home. Nonetheless, cost-effective technical options exist for substantially reducing energy requirements of existing homes. Storm windows, added insulation, clock thermostats, and retrofit heating system improvements have been considered conventional conservation measures for several years. Programs to encourage consumers to implement these conservation options have been carried out in a number of areas and have shown considerable success. One study of 40,000 retrofits monitored by U.S. utility companies in the early 1980s showed that energy consumption fell by 25% on average, and homeowners received a 23% return on their investments (Goldman, 1984).

Despite the favorable economics of some retrofit conservation measures, only a small portion of the potential energy savings from conservation retrofits has been realized to date. This is especially true in rental housing where the landlords do not perceive a financial interest in investing in retrofits. Also, low-income families, even if they own their homes, often lack the information or upfront capital to carry out cost-effective conservation measures. If conventional retrofit programs could be extended to larger percentages of existing housing stock, energy savings could be substantial.

Beyond conventional conservation programs, there are now more sophisticated options for improving the retrofit savings. Detailed measurements since the late 1970s have shown that existing homes have obscure defects in their thermal envelopes, leading to very large heat losses. Conventional walk-through energy audits are unlikely to identify these defects, nor would subsequent conservation retrofits correct them. New instrumented analysis procedures developed over the last few years can locate these defects quickly, but these instrumented audits are expensive compared with the standard energy audits now provided by many utilities.

On the other hand, many of the "hidden" defects, once detected, can be easily corrected at small cost. This has led to the development of the "house-doctor" concept as an alternative to traditional audits. For this type of audit a team of technicians conducts an instrumented audit and repairs many of the defects on the spot. One test of this concept showed average immediate energy savings of 19% from one-day "house-doctor" visits. Subsequent conservation retrofitting done at the recommendation of the house doctors increased the average energy reduction to 30%. The average cost of all retrofit measures was $1300 and the average real internal rate of return in fuel savings was 20% (See Goldemberg et al., 1988).

Another approach to improving residential and commercial energy efficiency has been proposed recently by researchers at Lawrence Berkeley Laboratory. Their approach is a reworking of the age-old concept of using shade trees to assist in cooling residential buildings. In their analysis the authors point out that in addition to the direct benefit in terms of reducing air conditioning loads at each house, the indirect effect of planting trees throughout an urban or suburban area can reduce the "heat island" effect, lowering ambient temperatures and further reducing air conditioning loads. In addition, of course, the trees directly remove CO_2 from the atmosphere, although the CO_2 reductions due to reduced cooling loads from well-placed trees are probably much greater than the CO_2 absorption by the trees (see Rosenfeld, 1988; Akbari et al., 1988). Los Angeles has announced a program to do this.

The advanced furnaces and heat pumps available for new homes could also provide significant benefits in the retrofit market. Economics of efficient equipment are generally more favorable as retrofits. Even after a retrofit shell improvement program, including the house-doctor approach, energy use in existing homes will remain well above the best levels achievable for new super-insulated homes. Thus, the added expense of sophisticated advanced heating and cooling equipment will be paid back much faster in energy savings.

In one example, existing homes that had already been visited by house doctors and had received associated shell improvements were evaluated for improved furnaces. Shell improvements were shown to have reduced gas use for space heating to about 70% of the previous requirement. Researchers estimated that retrofit of advanced condensing gas furnaces would further reduce space heating energy use to 44% of the original requirement. The estimated incremental investment (to replace a worn-out furnace with the 95% advanced furnace rather than a conventional 69% model) was estimated to average $1000 and result in fuel savings that correspond to a real rate of return of 15% (Goldemberg et al., 1988).

Commercial Buildings. Like residences, commercial and institutional buildings currently use significant amounts of energy, particularly for space conditioning and lighting. Opportunities for efficiency improvements also appear significant. Commercial buildings in recent years in the U.S. have used about 3.6 EJ of fossil fuels (mostly gas in the U.S. -- other OECD countries continue to heat a significant percentage of buildings with oil) and about 2.6 EJ of electricity (equivalent to about 8 EJ of primary energy) (Rosenfeld and Hafemeister, 1985).

Some progress is already being made in improving energy efficiency in commercial buildings. While surveyed commercial space in the U.S. increased by almost 10% between 1979 and 1983, total energy consumption actually declined by about 4%. Electricity consumption, however, increased in absolute terms as well as in share of total commercial energy use. Thus, the primary energy equivalent of commercial end-use energy consumption has increased (U.S. DOE, 1987a).

While progress has been made, it is evident that commercial energy use in the U.S. could still be reduced significantly with cost-effective efficiency measures. Estimated commercial energy use in the U.S. was about 3.0 gigajoules (GJ) [4] per square meter per year in 1980 (expressed as equivalent primary energy production). This figure is down from 5.7 GJ in 1973, but could still be greatly improved (Flavin and Durning, 1988.) One recent analysis estimated that energy use in standard new commercial buildings could be reduced by more than 50% below the current averages (Rosenfeld and Hafemeister, 1985).

As in the residential sector, traditional conservation measures, such as added insulation and window glazing, reductions in infiltration rates of outside air, passive solar energy concepts, and heat exchange between exhaust and incoming ventilation air are effective although less important. The traditional approach of tree shading, with its indirect heat island and CO_2 removal benefits, as discussed above, can also be applied to commercial buildings.

In addition, some more sophisticated techniques are cost effective for larger commercial buildings. New commercial building are being designed with "smart" energy management systems. These computerized systems monitor outdoor and indoor temperatures, levels of sunlight and location of people in the building. The system can then allocate heating, cooling and ventilation efficiently (Brody, 1987).

---

[4] GJ = gigajoule, 1 gigajoule = 10^9 joules.

Another advanced technique being applied for commercial energy efficiency is thermal storage. In this case, some storage medium, such as a body of water, is used to store heat or cooling when it is readily-available and then release the warm or cool air later when it is needed. This concept has been used in new commercial buildings in Sweden, storing heat energy from people and equipment, and in Nevada to chill water with cool night air and use the chilled water to offset the need for air conditioning during the day (Rosenfeld and Hafemeister, 1985).

Window technology is also improving rapidly. A special "heat mirror" film, which doubles the insulation value of windows, is now commercially available. The film is designed to let light in without allowing heat to escape. Another available technology is to create a vacuum in the space between two panes, creating a "thermos" effect. These and other advanced technologies may allow commercially-available windows in the 1990s to have the same insulating value as ordinary walls (Brody, 1987; Selkowitz, 1985).

As was the case with residences, many of the advances in energy efficiency for new commercial buildings are transferable to retrofit applications to a lesser degree. A study conducted some years ago attempted to estimate the potential energy savings available from retrofits of existing commercial buildings. The conclusion drawn from a survey of several experienced engineers and architects was that a target of a 50% reduction in energy use in U.S. commercial buildings by the year 2000 was reasonable (SERI, 1981).

More recently, Amory Lovins and others at the Rocky Mountain Institute conducted a detailed analysis of the retrofit potential of commercial buildings in the Austin, Texas, area. This study identified potential savings in electrical energy that totaled 73% of the buildings' current energy use (for lighting and other equipment as well as space conditioning). The cost of these measures was estimated to be lower than the operating costs of existing powerplants (Rocky Mountain Institute, 1986), although, there is some question as to what proportion of these savings could be achieved in practice.

Indoor Air Quality

One of the concerns about increasing the energy efficiency of buildings is the increase in indoor air pollution that can result, primarily from efforts to reduce air infiltration. Most homes in the U.S. have air exchange rates, on average, of more than one change per hour, meaning all the air in the house is replaced by outside air once each hour. As new homes are constructed more tightly and some older homes are retrofitted with vapor barriers and better seals around doors and windows, the air exchange rate drops. Without additional ventilation measures, concentrations of several harmful pollutants, including radon gas, formaldehyde, combustion products from tobacco smoke and wood stoves, and asbestos particles, can reach harmful levels.

Control strategies for these forms of indoor air pollution include air cleaning, local ventilation, mechanical ventilation with heat recovery, and exhaust ventilation with heat pump heat recovery. Heat recovery or air-to-air exchange systems have become more popular as homes have become better insulated and more tightly sealed. These can ensure the generally-accepted minimum standard of about 0.5 air changes per hour, while reducing heat loss by using the heated exhaust air to warm the incoming fresh air. Unfortunately, the cost of these systems are high and studies in Canada suggest that their efficiencies may be lower than manufacturers have claimed (Hirst, 1986). This may be due in part to improper maintenance by homeowners. The systems, which usually draw air continuously and can have problems with condensation forming in the heat exchanger, require more routine maintenance than the average homeowner is accustomed to devoting to a major appliance. The use of exhaust ventilation systems connected to an air or water heat pump is a new technological approach that may hold some promise for improving cost-effectiveness and improving some of the maintenance issues. They are being developed primarily in Sweden.

Lighting

Lighting consumes about 20% of U.S. electricity use, most of it in residential and commercial buildings. This end use offers some of the most cost-effective opportunities for saving energy. One study has estimated that 40 large U.S. powerplants could be replaced by simply implementing currently-available, cost-effective lighting efficiency improvements (Rosenfeld and Hafemeister, 1985). Cutting electricity use for lighting in industrialized countries by three quarters has been proposed as a reasonable goal (Flavin and Durning, 1988). Box 7-4 describes several key advanced lighting technologies.

A number of currently commercial measures, implemented in combination, can achieve dramatic energy reductions--over 75% in commercial/institutional settings. These measures include improved controls, reflectors, spacing of lighting, and more efficient bulbs and ballasts. The University of Rhode Island reported reductions of 78% in lighting energy after implementing such a program. The cost of saved energy was calculated to be less than 1 cent per kilowatt-hour (New England Energy Policy Council, 1987). An added benefit of lighting improvements in warm climates is that more efficient lighting reduces waste heat and, therefore, air conditioning loads. The California Energy Commission has estimated that in Fresno, every 100-watt savings in lighting reduces air conditioning energy requirements by 38 watts (Rocky Mountain Institute, 1986).

BOX 7-4 INCREASING LIGHTING EFFICIENCY

Research and development into energy efficient lighting and design features has produced a constant stream of new products and advances. Below are brief descriptions of several of the areas where major advances have taken place.

- Compact Fluorescent Lamps: Compact fluorescent lamps are designed to be screwed into a standard light socket and thus have begun to compete directly with incandescent bulbs. Because they are 60-70% more energy-efficient than incandescent (Hirst, 1986) and are beginning to gain wider acceptance, they represent potentially significant energy savings. If compact fluorescent replaced all incandescent lighting, it is claimed that they could displace 7.5% of total electrical consumption in the U.S. (Lovins and Sardinsky, 1988).
- High Intensity Discharge (HID) Lamps: These are designed primarily for warehouses, factories, street lighting, etc. Three types of HID lamps are currently in use: high pressure sodium, low pressure sodium and metal halide. High pressure sodium and metal halide give approximately 45-60% savings over mercury vapor or fluorescent lighting. Low pressure sodium is somewhat more efficient, but its intense yellow light can be undesirable for many applications. (Hirst et al., 1986).
- Electronic Ballasts: In conventional fluorescent lights the voltage required for operation is provided by an electromechanical ballast which itself consumes a portion of the energy used. New electronic ballasts reduce this additional power consumption by 20-35% (Hirst et al., 1986), and, because of their smaller size, are a key factor in the emergence of compact fluorescent.
- Daylighting: Daylighting is a design approach which enhances the use of natural light either from windows, sidelighting, clerestories, monitors and skylights, or from the use of light pipes or optical fibers to transmit light to the location needed. The use of light colored paints and light shelves helps to distribute the light into the building interior.
- Additional Advances: Several other advances in lighting technology and design deserve mention. One advance is specular ("mirrorlike") reflectors which increase total reflectivity, direct the light in a more optically favorable direction, and maintain their high reflectivity significantly longer. Lighting controls, which include time clocks, scheduling controls, personnel or occupancy sensors, and daylighting sensors, reduce power consumption by turning off lights when they are not needed. Task lighting improves efficiency by directing light onto the specific task area where it is needed most, rather than lighting entire areas.

Appliances

After space conditioning and lighting, remaining energy uses in residential and commercial buildings are largely associated with large appliances. Opportunities for significant energy efficiency improvements in this category have been well-documented. Table 7-4 illustrates some of these opportunities. U.S.-made refrigerators, for example, currently average 1450 kilowatt-hours per year. The best currently commercial model in the U.S. uses about half that much energy. A recent study calculated that efficient new refrigerator freezers that would use about 200 kilowatt-hours per year, or less than 15% of the current average use, could be cost-effectively produced (Goldstein and Miller, 1986). Water heaters also account for a large percentage of appliance energy use. The potential for energy savings is significant through the use of the most efficient technologies and also by switching from electricity to gas. Other energy-intensive appliances also provide opportunities for energy savings. As shown in Table 7-4, the potential exists for advanced technologies that could be produced in the 1990s that are at least 50% more energy efficient than the 1986 average for all major energy-using residential appliances (Geller, 1988).

Near-Term Technical Options: Developing Countries

In developing countries markedly different strategies may be necessary to address residential and commercial energy services. In many developing countries there are distinct modern and traditional sectors. In the modern sector, energy-use patterns are very similar to those in industrial economies (adjusted for climate differences). Commercially-marketed fossil fuels and electricity provide the energy input for a similar mix of energy services: space conditioning, water heating, lighting, and appliances for cooking, refrigeration, entertainment, etc. This modern sector, however, is often smaller than the traditional sector, which exhibits completely different energy-use patterns.

TABLE 7-4

Summary of Energy Consumption and Conservation Potential with Major Residential Equipment

Product	1986 Stock UEC[a]	1986 New UEC[b] (kWh/yr or therms/yr)	1986 Best UEC[c]	Advanced technology for 1990s[d]
Refrigerator	1450	1100	750	300-500
Freezer	1050	750	430	200-300
Central AC	3500	2900	1800	1200-1500
Room AC	900	750	500	300-400
El. water heating	4000	3500	1600	1000-1500
El. range	800	750	700	400-500
El. clothes dryer	1000	900	800	250-500
Gas space heating	730	620	500	300-500
Gas water heating	270	250	200	100-150
Gas range	70	50	40	25-30

---

[a] Unit energy consumption per typical installation in the 1986 housing stock.

[b] Unit energy consumption for the typical model produced in 1986.

[c] Unit energy consumption for the best model mass-produced in 1986.

[d] Unit energy consumption possible in new models by the mid-1990s if further cost-effective advances in energy efficiency are made.

Source: Geller, 1988.

The energy sources in the traditional sector are largely "noncommercial" biomass, used primarily for cooking and space heating in some colder or high-altitude regions of developing countries. Also, fossil fuels (e.g., kerosene) are frequently used for lighting. (In China, unlike most other developing countries, coal is also used for residential cooking and space heating in the traditional sector.) The task of development projects in these poorer sectors is to vastly increase the level of energy services available for residential and commercial applications. Altruism and development objectives aside, this approach can contribute significantly to solving the climate warming problem because many developing countries have used fuelwood to such an extent that they have become net consumers of forests, and global deforestation is one of the significant causes of increasing greenhouse gas concentrations. The important issue from a climate perspective is to increase energy services without increasing greenhouse gas emissions.

As the developing countries continue to increase their per capita energy use, the implications in terms of energy use and greenhouse gas emissions are enormous. It is technically possible, however, for developing countries to substantially increase per capita energy use without substantially increasing fossil-fuel use. Emissions-reducing strategies similar to those proposed for industrialized countries can be promoted in the modern sectors of the developing countries. However, strategies suitable for the traditional, poorer sectors must be integrated into ongoing development programs if they are to be accepted by the local population. Technical options for reducing greenhouse gas emissions must not only be efficient, they must also be designed to increase energy services to these poorer sectors.

Increasing Efficiency of Fuelwood Use

The primary use of biomass energy in developing countries is in residential cooking, traditionally done in inefficient and smoky conditions. The inefficiency of combustion exacerbates deforestation, and leads to increased time and effort devoted to gathering fuelwood (and fodder), and the smoky combustion results in exposure to significant emissions of health-damaging air pollutants.

Recognition of these problems has focused a great deal of attention on improving the cookstove as a low-cost solution. Existing cookstoves have efficiencies only on the order of 10%. Relatively simple improvements in stove design can in theory reduce wood requirements by 35-70% (Goldemberg, et al., 1987). However, getting people in developing countries to accept and use better-designed stoves has proved difficult for a number of reasons (Miller, et al., 1986). In spite of spirited efforts by a number of groups and generous grants by international aid agencies, traditional cooking stoves and practices have proved surprisingly difficult to dislodge. Traditional stoves come in a bewildering variety of designs and materials and have evolved to suit local fuels and diets. They perform a multitude of functions that were not considered by the early "improved" stove designers and promoters. Failure of the newer designs on some of these dimensions often hampered their acceptance. Current programs represent the third generation of improved designs (Smith, 1987).

There are currently half a dozen examples of successful dissemination efforts. Notable dissemination programs are in place in West Africa, in Kenya and in Karnataka, India (Baldwin et. al., 1985). Successful designs are backed by sound principles of heat transfer (Baldwin, 1987); are targeted to a particular region, generally where cooking fuel is traded; require no substantial behavioral modification from users; and are provided with follow-up support.

Fuel savings with improved stoves, predicted on the basis of laboratory water-boiling efficiency tests, have invariably proved to be over-estimates for field conditions. If fuel savings observed in the laboratory were directly transferable to the field, an improved stove with 40% efficiency would result in a 75% fuel saving when it replaced a traditional stove with 10% efficiency. Yet only a few programs have reported fuel savings, at best on the order of 20%, though greater savings could be possible with better-run programs.

Even with existing limited efficiencies, where fuelwood is traded the payback period is on the order of a few months and therefore economically attractive (Manibog, 1985). As Williams (1985) points out, the adoption of such stoves is a far more cost-effective method of dealing with the fuelwood crisis than any "supply-oriented" solution to the problem that emphasizes growing trees for fuel.

Widespread introduction of improved stoves, while reducing total emissions of oxides of carbon per cooking task, will change the ratio of CO_2:CO emitted. This ratio on a mass basis for traditional stoves is perhaps close to 10:1, whereas for more efficient stoves, this could be reduced to 5:1 reflecting the more complete combustion in traditional stoves. Although CO is not a radiatively interactive gas, it does interact with hydroxyl ions; as a result, its presence affects the concentration of methane and ozone in the troposphere (See **CHAPTER TWO**).

Substituting More Efficient Fuels

In the traditional sectors of many developing countries, substitution of fossil-based end-use technology for traditional biomass use may be desirable as part of a larger strategy even though it may directly increase greenhouse gas emissions to a small degree. Gaseous fuels (natural gas, LPG, etc.) are very attractive relative to fuelwood for several reasons, including their vastly superior convenience and controllability. In addition, a well-designed gas-fueled stove can be five to eight times more efficient than traditional firewood stoves (Goldemberg et al., 1988). Thus, the shift to gaseous cooking fuel can decrease the demand for fuelwood, which can slow the rate of deforestation, or free up vast amounts of fuelwood for use as a feedstock for advanced biomass energy systems, or both. In a few developing countries, such as China, coal is used for cooking and space heating; the advantages discussed above for gaseous fuels also apply as a replacement for coal (with associated reductions in greenhouse gas emissions).

In the traditional sectors of many developing countries, lighting frequently is achieved with very inefficient combustion technologies. In India, for example, it is estimated that 80% of the households illuminate with kerosene lamps. The efficiency of illumination of these lamps is very low. Providing the same level of illumination with incandescent electric bulbs would be 200 times more efficient at the end use (Goldemberg et al., 1988). (Of course, the availability of electricity might actually allow a much greater level of illumination in homes). Thus, even if the electricity production is only 30% efficient, and is coal-fired (worst-case assumptions), the equivalent electric lighting would still produce less net CO_2. If the most efficient current compact fluorescent lighting were used, the benefit would be even greater. Of course, the major constraint to substituting electricity for fossil fuels is the limited availability of electricity in developing countries. Small-scale local generation based on renewable technologies could make major contributions in this situation. These and other options for increasing electricity in developing countries are discussed in **PART TWO: ENERGY SUPPLY.**

Retrofit Efficiency Measures for the Modern Sector

For those residential and commercial segments of developing countries that have similar characteristics to industrialized countries, many of the same retrofit efficiency measures are appropriate. In fact, it is likely that many retrofit measures would be more effective in developing countries. As pointed out in a recent U.S. AID study (1988b), while "industrialized countries have made major strides in using electricity more efficiently over the last decade, few achievements have been made in developing countries in using electricity more efficiently. The opportunities for improvements are tremendous, and the cost is only a fraction of the generation expansion option." In addition, air conditioning requirements are generally heavier in tropical developing countries.

Thus, improvements in building shells and air conditioning equipment could be very effective in reducing electricity use. Similarly, the air conditioning benefit (due to less waste heat) of improved lighting would also be greater in developing countries.

A recent study of Pakistan identified cost-effective efficiency improvements that could reduce commercial sector electricity use by over 30%. Based on commercially available improvements in lighting, air conditioning and fans, and thermal insulation, the study projected national savings of 1800 MW of generating capacity and 18,200 GWh of electricity generation (U.S. AID, 1988b). An analysis in Brazil indicated the potential to reduce electricity use for lighting by 60% in many commercial buildings (Geller, 1984).

New Homes and Commercial Buildings

It is expected that rapid expansion of the residential and commercial building stock will occur in conjunction with economic development in the developing countries over the coming decades. Use of the efficiency options discussed for industrialized countries, adapted to local conditions and objectives, could minimize the increases in energy use associated with this growth. Obviously, since the rate of construction of new building space (and distribution of appliances, etc.) will be much higher in developing countries, the importance and potential impact of efficiency measures will be proportionately greater as well.

Several recent studies have identified significant potential for reductions in energy use in new commercial buildings in developing countries (see, for example, Turiel et al., 1984, Deringer et al., 1987). Careful use of daylighting alone has the potential to reduce energy use by roughly 20% relative to the current building stock in Singapore (Turiel et al., 1984). Other important improvements include efficient lighting systems, external shading, and size and placement of windows.

Near-Term Technical Options: Soviet Bloc Countries

Energy use in buildings in the Soviet Union is dominated by space heating. 25% of the population live in a climate which experiences from 210 to over 300 heating days per year. An additional 40% live in a climate characterized by a 180-280-day heating season (Tarnizhevsky, 1987). Since the early 1970s, the Soviets have made dramatic progress in improving energy efficiency in specific applications, "in large energy uses easily identified and controlled by the planning apparatus" (Hewitt, 1984). The dominant approach advocated by Soviet researchers for space conditioning is consistent with this experience. Centralized, or "district" heating systems, have been the preferred approach to space heating for some time. By 1980, about 70% of residential and commercial heat demand in cities and towns was provided by central systems. Sources of heat for these systems are primarily cogeneration from both fossil-fueled and nuclear powerplants and some waste heat recovery from large industrial process heat uses (e.g., ferrous metal, chemicals, and petrochemicals) (Tarvarshy et al., 1985). Plans for improving energy efficiency include 1) further replacement of local heat sources with district heat from cogeneration, 2) weatherization of buildings, and 3) reductions in heat losses in distribution networks (Tarnizhevsky, 1987).

Electricity consumption in buildings is also growing in the Soviet Union, principally for lighting and household appliances (including some electric ranges). The most significant sources of growth from 1975-1985 were attributed to increasing proliferation of household applications associated with improving living standards. One Soviet researcher estimated that significant electricity savings are achievable through manufacture of more energy-efficient appliances and lighting, optimized use of lighting, elimination of known losses or "wastes" of electricity, etc. (Tarnizhevsky, 1987).

Summary of Near-Term Technical Potential in the Residential/Commercial Sector

In summary, it appears technically feasible with today's technology to reduce space conditioning energy requirements in new homes to 50% of the current average for new homes. Retrofits of existing homes could reduce space conditioning energy use by an average of 25% with the "house-doctor" approach. Reductions of energy use in existing commercial buildings by at least 50% may be technically feasible, and new commercial buildings could easily be 75% more efficient than the average U.S. commercial building. In 1985 the U.S. consumed about 15.3 EJ of energy (primary energy equivalent) in residential and commercial space conditioning (U.S. DOE, 1987a). Retrofits to existing stock could save at least 4 EJ.

Projected estimates for the climate scenarios show residential and commercial energy use in the U.S. and in the OECD as a whole remaining roughly constant through 2025. With rapid widespread penetration of the most efficient new buildings, instead of gradual improvement, the growth in energy consumption from new buildings could be greatly reduced.

Based on potential energy savings of more than 60% for almost all types of appliances, a 50% overall reduction in appliance energy use by the year 2010 is technically feasible. To achieve this reduction would require aggressive policy actions that would ensure that all appliances produced in the next decade be as energy efficient as the best current technology can produce and that would encourage rapid turnover of existing appliances. Current energy use from such appliances is in the range of 7.4-8.4 EJ (expressed as primary energy equivalent).

With aggressive programs to improve energy efficiency in residential and commercial buildings, it appears technically feasible to reduce projected U.S. energy use in this sector by at least 50% in the year 2010. This is roughly equivalent to the reduction assumed in the policy scenarios by 2025.

The technical potential in the OECD as a whole is probably close to that of the U.S. Although more detailed analysis is required, preliminary indications are that the technical potential to reduce projected residential and commercial energy in the much more rapidly growing developing countries and in the Soviet bloc countries is even greater than that estimated for industrialized countries.

Long-Term Potential in the Residential/Commercial Sector

In the long term, the potential for reducing energy use in buildings is considerable. The majority of current per capita energy consumption in buildings could be eliminated over the long run by simply incorporating the best currently-available building and equipment technologies into housing and commercial building stock as it is expanded and replaced over the next 50-100 years. Further efficiency improvements could come from emerging technologies and broader application of existing technologies. In space conditioning, examples include "smart windows" which sense light and adjust opacity to utilize solar heat and light most effectively, and new building materials which may provide better insulating qualities at a reduced cost. Existing technologies for large buildings, such as use of thermal storage and computer controls, could be applied to small buildings and residences as well.

As improved building and equipment technologies are incorporated over time, space conditioning will probably become a much smaller component of total building energy use. Appliances and information technologies (computers, telecommunications) may become more important determinants of residential and commercial energy consumption. Advanced technologies may provide comparable or improved services with less energy. For example, some experimental concepts have been developed for storing food that might greatly reduce the need for refrigeration. As information technology continues to evolve, it may well provide improved energy efficiency as a byproduct, as has been the case in the evolution from vacuum tubes to semiconductors to integrated circuits.

Alternative fuels could also play a more important role in buildings over the long term. Advances in solar photovoltaic technology may make it economic to generate most or all of the needed electricity locally. Hydrogen may become an energy option for building energy needs utilizing or adapting existing infrastructure for distribution of natural gas (See **PART TWO: ENERGY SUPPLY**).

INDUSTRIAL SECTOR

Industrial end uses account for the largest single component of energy use in the industrialized countries--almost 43% of the energy consumed in the OECD in 1985 (in primary energy equivalent terms [U.S. DOE, 1987b]). Actual secondary energy consumption was about 36%. In developing countries, if agriculture is included as part of industry (as it is in this chapter), then the industrial sector generally consumes an even higher percentage of total commercially-traded energy. In developing countries as a whole, industrial energy makes up almost 60% of total modern energy use. In the Soviet bloc, the percentage is slightly under 50% (see **CHAPTER IV**), but in the scenarios this proportion declines over time, accounting for only 36-40% by 2025.

Industrial use is also an area in which impressive efficiency gains have been observed in recent years. In the United States, for example, "end-use energy consumption per constant dollar of industrial output declined by 28% between 1974 and 1984 - reflecting substantial improvements in energy efficiency as well as the relative decline in output from energy-intensive industries in this country" (U.S. DOE, 1987b).

Several researchers have documented the components of changing industrial energy use in developed countries (see Ross, 1984 and 1986; Goldemberg et al., 1987; and Williams et al., 1987). One significant component of declining industrial energy use is a structural shift to products that are inherently less energy-intensive to produce. It is now a well-documented phenomenon that as industrialized countries proceed beyond a certain level of economic development and affluence, their per capita consumption of some of the most energy-intensive industrial products (e.g., cement, steel, and durable goods) declines. Thus, having approached "saturation" in many energy-intensive products, industrialized countries will likely continue to consume less energy per dollar of GDP in the future as incomes continue to rise.

The other major component of declines in energy intensity over the past decade and a half has been actual improvements in the efficiency of production processes. Energy price shocks of the 1970s often affected industrial energy users more than other sectors. As stated by Goldemberg et al. (1988): "Because the cost of providing them energy involves much less unit transport and marketing cost, industrial users are more sensitive than other energy consumers to cost increases at or near the point of energy production." In addition, industrial users, particularly where energy costs are a significant component of product cost, tend to be more aware of and responsive to the return on investments in energy efficiency than are customers in other sectors. Ross (1986) has noted many cases in which industrial managers have pursued aggressive efficiency improvement policies in response to the price signals of the 1970s.

Efficiency improvements to date have largely been in a few industries that are the most energy intensive: petroleum refining, chemicals, cement, metals, pulp and paper, glass, clay, etc. (See Table 7-5). There is reason to believe that efficiency improvements will continue rapidly in the future in the energy-intensive sectors of industry in the developed countries. It is also expected that the structural shifts to less energy-intensive products will also continue in these countries (Williams et al., 1987). Technical options may exist for accelerating these trends and also taking advantage of additional efficiency improvements possible in other industries. Evidence exists that economically-attractive energy conservation investment opportunities exist in industries outside of those few that

TABLE 7-5

Reduction of Energy Intensity[a] In the Basic Materials Industries (1972-1983)

	Percent
Chemicals[b]	31
Steel	18
Aluminum	17
Paper[c]	26
Petroleum refining[d]	10
Energy Weighted Reduction	21

[a] Generally energy per pound of product, unadjusted for environmental and other changes. Purchased electricity accounted for at 10,000 Btu/kwh (2.5 Mcal/kwh).

[b] Not including fuels used as feedstock.

[c] Not including wood-based fuels.

[d] Changes in inputs and outputs and environmental regulations have had a particularly strong impact on petroleum-refining energy. Adjusted for such changes, energy intensity was reduced 26%.

Source: Ross, 1985.

are energy-intensive. For a number of reasons these investment opportunities are often being overlooked (Ross, 1984, 1986).

In contrast to industrialized countries, the developing countries generally are in the midst of, or beginning, a period of rapid expansion of energy- and materials-intensive industries to raise per capita income levels. In addition, industries in these countries currently use energy far less efficiently than do similar industries in industrialized countries. In many cases, this is related to the government's subsidizing of energy prices, lack of access to the most modern technologies, and lack of management skills for identifying and implementing efficient options (Flavin and Durning, 1988). If developing countries industrialize without dramatically improving energy efficiency, the result would be enormous increases in industrial energy use.

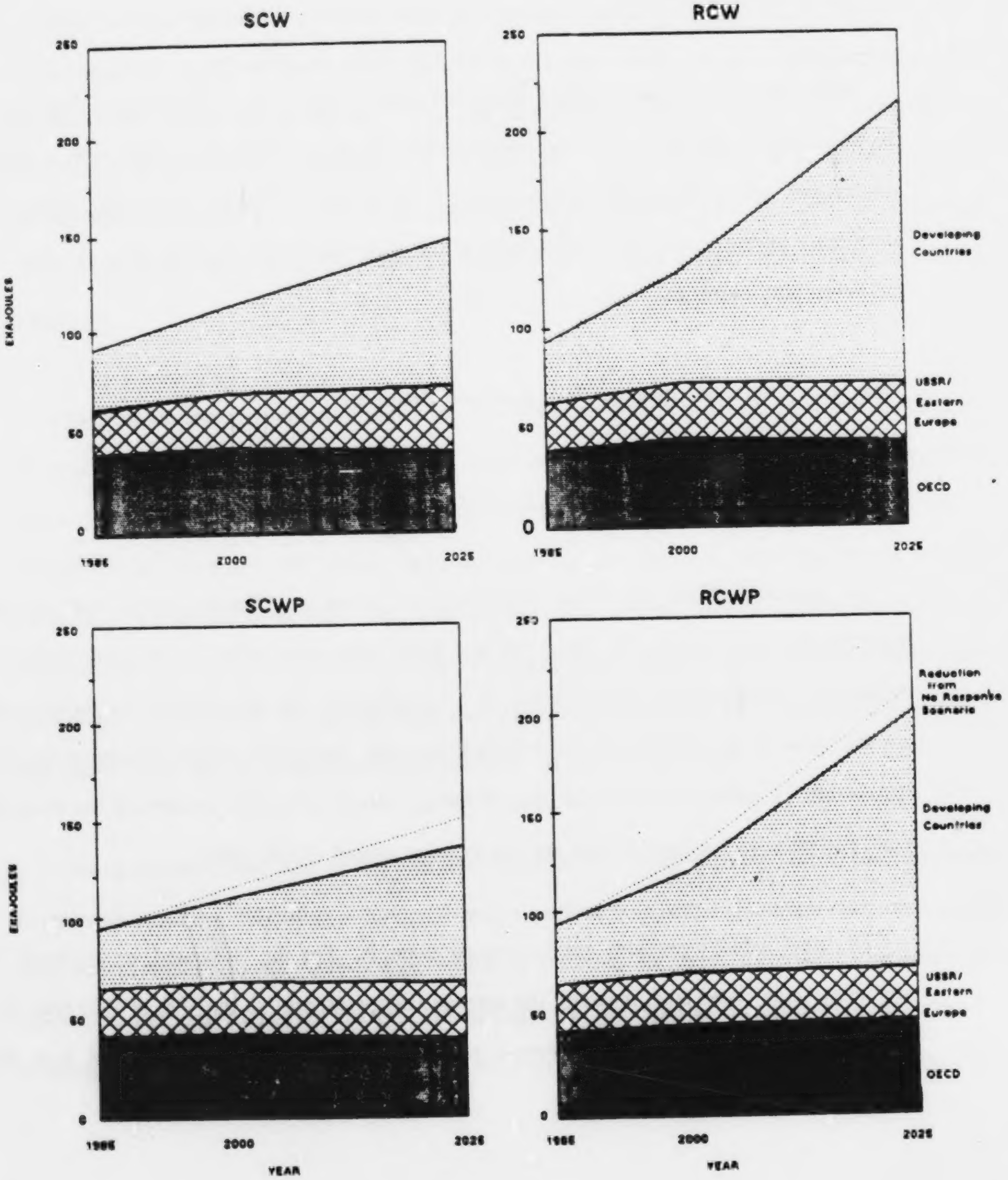
The No Response scenarios indicate the potential for extensive growth in industrial energy use by 2025. Figure 7-9 illustrates these results and also shows that the overwhelming majority of growth in this category (81-92%) occurs in developing countries. As these countries develop industrial infrastructure and as their standards of living rise in the future, the energy requirements for the production of basic industrial materials could be enormous.

There is a widening recognition, however, that this type of growth may not be sustainable, and may indeed become self-defeating. Continuing along current energy-intensive industrial development paths may result in increases in energy imports, which absorb foreign exchange credits that are needed for further development. Local environmental concerns and capital scarcity may also constrain the conventional industrial development option. Developing countries and development assistance organizations are now focusing much more attention on the energy consequences of industrial development decisions.

FIGURE 7-9

INDUSTRIAL ENERGY USE BY REGION

(exajoules)



Technical options may exist for "leapfrogging" from current obsolete energy-inefficient technologies directly to very advanced efficient technologies in some developing countries (although new policy actions will be required; see **CHAPTER IX** of this report). In addition, opportunities exist for designing industrial development based on locally-available alternative fuels, which has been initiated in some developing countries.

These options are poorly defined as yet and clearly require more detailed attention. As a result, the Stabilizing Policy scenarios incorporated in this report are somewhat conservative in terms of the assumptions about efficiency improvements. As shown in Figure 7-9, these scenarios result inefficiency improvements of 6-10% overall in the industrial sector by 2025, most of which occurs in the developing countries.

Near-Term Technical Options: Industrialized Countries

Accelerated Efficiency Improvements in Energy-Intensive Industries

As discussed above, significant improvements in energy efficiency were made in the basic materials industries during the late 1970s and early 1980s (see Table 7-5 for improvements in key industries). Despite these improvements, in most industries the opportunities for further reductions are still quite large. This is true for two basic reasons. Industrial process technology has improved significantly in recent years, and the pace of energy-related technology investment has been relatively slow, particularly in industries that are not growing overall (Ross, 1988).

The steel industry provides one interesting example. For the integrated, or ore-based industry (excluding scrap-based steel making), the average energy intensity in the U.S. in 1983 was about 31.2 GJ per ton (Ross, 1987). The reference plant documented by the International Iron and Steel

Institute (1982) would consume about 19.2 GJ per ton producing roughly the same mix of products. Thus, replacing existing U.S. technology with the best currently commercial, cost-effective technology would produce a 39% savings.

More energy-efficient technologies, once proven commercially, will likely be extremely attractive on the basis of cost-effectiveness, including improvement in overall process cost and environmental impact as well as energy efficiency. Thus, the marketplace can be expected to encourage all producers to adopt advanced technologies in the long run. From the perspective of climate warming, the important concern is whether there are opportunities for accelerating this turnover, either through research initiatives or through programs to promote more rapid capital replacement in selected industries.

Other major energy-consuming industries--petroleum refining, chemicals, pulp and paper, etc.--are also undergoing transformations that will result in continuing declines in energy intensity in the future. Quantifying the potential energy efficiency improvements in each major industry and in various OECD countries will require more detailed analysis than has been carried out to date. Technically-feasible improvements (e.g., assuming that each industry average improves to match the energy efficiency of the best currently-available or emerging technology) could be much greater. With the exception of primary aluminum, other energy-intensive industries have even greater technical opportunities for energy conservation than the steel industry (Ross, 1988).

One important component of the technical potential for reducing energy use in basic industries is materials recycling. Recycling of inorganic wastes, such as bottles and aluminum cans, saves energy and reduces waste streams. Substituting recovered materials for virgin materials to produce steel, aluminum, and glass conserves energy. Depending upon the types of materials recycled, estimates of energy savings can range from an average of 5 GJ per ton of material recycled (Gordon, 1979) to 25 GJ per ton (Stauffer, 1988).[5] Recycling 24 million tons of paper, cardboard, glass, and aluminum (about 16% of our current waste stream) could result in savings of up to 0.6 EJ (Stauffer, 1988).

Unfortunately, economic policies discourage recycling and the use of recycled materials. Differentials in transportation rates favor virgin loads over secondary loads, and favorable tax treatment toward production from virgin materials continues to make recycled materials more expensive to use. If these policies were eliminated or reversed (e.g., creating incentives to boost demand for recycled products), the technical potential for energy savings is quite large. Increased recycling would also have the added benefit of reducing waste.

Aggressive Efficiency Improvements of Other Industries

While there is clearly measurable progress in the energy-intensive, and therefore energy-price-sensitive, industries, less progress has been made in energy efficiency in other industries. Industries for which energy is not a major component of product cost frequently pass up opportunities for investing in energy efficiency with high estimated rates of return (Ross, 1984).

The technical potential for energy savings could be important for widespread penetration of just a few energy-saving measures. The Electric Power Research Institute estimates that 95% of industrial electricity use is represented by three major applications: electromechanical drives or motors, 70%, electrolysis, 15%, and process heat, 10% (Kahane and Squitieri, 1987). Recent studies have estimated that cost-effective replacement of motors and the addition of variable-speed drives could reduce total electricity use in motors by as much as 17% in some regions (Geller et al., 1987; Alliance to Save Energy, 1987).

---

[5] PJ = petajoule; 1 petajoule = 10^{15} Joules.

Comparable efficiency improvement measures have also been identified for the other major components of industrial electricity use (Kahane and Squitieri, 1987). In addition, many of the efficiency measures identified earlier for lighting and space conditioning in large commercial buildings are also applicable to industrial users. A recent study examined electricity-saving projects currently being undertaken in automobile manufacturing plants in the U.S. and Europe. It shows that roughly 30% savings from the current cost of purchased electricity are being achieved (Price and Ross, 1988).

Cogeneration

Technologies for cogeneration--production of electricity and heat or steam for other useful purposes from a single combustion source--are described in **PART TWO: ENERGY SUPPLY**. The primary market for cogeneration is in large industrial facilities (although large commercial/institutional applications are important in the Eastern Bloc and are also beginning to be seen in the U.S.). From industry's perspective, cogeneration is one method for improving energy efficiency. The industrial facility benefits, either in the form of electricity used on-site or revenues from sales of electricity to the local utility, from the fuel it would otherwise have consumed solely for industrial production purposes.

Industrial cogeneration has grown rapidly in the U.S. since the 1978 passage of the Public Utilities Regulatory Polices Act (PURPA), which ensures that cogenerators (among others) can sell electricity to utilities at the utilities' avoided cost (the cost that the utility would otherwise have to pay to produce or obtain the electricity). As of 1985, 13 gigawatts of cogeneration capacity were in operation (Edison Electric Institute, 1985). Projects that would yield an additional 47 gigawatts have been registered with the Federal Energy Regulatory Commission (FERC) through October 1987 (FERC, 1988). One company specializing in cogeneration has estimated that cogeneration capacity could reach 100 gigawatts (equal to about 15% of current capacity) by the year 2000 (Naill, 1987).

All of these projects tend to reduce potential greenhouse gas emissions as they result in more efficient use of energy. To the extent that industrial cogeneration projects are based on natural gas or oil--or industrial waste products such as black liquor or bark in pulp and paper--and displace new coal-fired electric generating capacity, the net impact on greenhouse gas emissions (as well as local environmental loadings) could be much greater.

Near-Term Technical Options: Developing Countries

As noted above, developing countries generally are in the early stages of a rapid expansion in producing energy-intensive materials associated with infrastructure development and widespread access to basic consumer durables. If this process proceeds along the path experienced historically by the industrialized countries, the increases in energy consumption and CO_2 emissions will be enormous. In fact, the need to import fossil fuels to support rapid expansion of heavy industry could become self-defeating, operating as a brake on the rate at which some developing countries can industrialize.

Understandably, developing countries and development assistance organization are concerned about alternative approaches to industrial development that would allow developing countries to increase economic activity without having to devote ever-increasing shares of their foreign exchange earnings to financing fossil-fuel imports. Several possible strategies for achieving this goal are very compatible with concerns about long-term greenhouse warming.

Technological Leapfrogging

This phrase has been used by Goldemberg et al., (1987) in discussing industrial development options for both industrialized and developing countries. Theoretically, at least, developing countries could adopt the most efficient process technologies currently available, or even push ahead with currently-experimental technologies as they invest in major expansions of heavy industry necessary to foster economic development. If this strategy were implemented, the projected massive increases in industrial energy use in the developing countries would be significantly reduced.

There are a number of reasons why this may not occur in practice. Because capital (and entrepreneurial experience) is scarce in developing countries, there is a tendency to avoid risky investments. Conventional wisdom suggests that these countries should adopt technologies that are already "mature" in the industrialized countries. This "conventional wisdom" has affected decisions both by developing countries themselves and by relatively conservative leading institutions (banks or assistance organizations) called upon to provide capital. Often, though by no means always, advanced energy-efficient technologies require larger capital investments than older technologies. Also extremely important is that the availability and cost of certain components of production--labor, capital, and natural resources--vary widely between developing countries and industrialized countries, and among individual developing countries. Since many developing countries have difficulty raising the capital required for many investments, some form of international financial arrangements may be necessary to ensure that developing countries adopt energy-efficient technologies as they industrialize (see **CHAPTER IX** for further discussion).

Thus, developing countries will have difficulty basing rapid industrial development on currently mature, but also relatively energy-intensive, technologies available from the industrialized countries. On the other hand, "leapfrogging" to the most advanced technologies now being developed in industrialized countries may be inappropriate in terms of the local availability of labor, capital, and natural resources. What appears to be needed is to identify and develop advanced industrial process technologies that are appropriate to each developing country's individual endowment of resources. To the extent that developing countries move in this direction, energy efficiency, or at least efficiency in fossil-fuel use, should be a major characteristic of the desirable options for most developing countries.

Alternative Fuels

As discussed above, most developing countries are interested in limiting increases in fossil-fuel imports associated with industrialization. For this reason, they will undoubtedly provide a proving ground for development of heavy industry based on alternative fuels.

One option for some developing countries may be to develop potential hydroelectric generation resources and base industrial development on advanced electricity-intensive processes (Opportunities and difficulties in developing hydroelectric generation are discussed in more detail in **PART TWO: ENERGY SUPPLY**). In general, developing countries are relatively rich in biomass resources and in some cases undeveloped hydropower, while they are net importers of fossil fuels. Thus, the tailoring of industrial development strategies to local resources will likely reduce greenhouse gas emissions in addition to achieving other benefits.

For those developing countries with abundant coal resources, most notably China, there may be a tradeoff between energy self-sufficiency goals and climate warming concerns. Even in these situations, promoting the most energy-efficient technologies should be a common goal. When developing countries have both natural gas and coal resources, local environmental and economic concerns, including consideration of the greenhouse phenomenon, should all encourage a near-term emphasis on natural gas.

Retrofit Energy Efficiency Programs

A recent report by the U.S. Agency for International Development (U.S. AID, 1988b) reviewed the electricity supply-and-demand situation in a number of developing countries. The report documented serious concerns in many developing countries about current or projected shortages in electricity. However, it also found that "few achievements have been made in developing countries in using electricity more efficiently. The opportunities are tremendous, and the cost is only a fraction of the generation expansion option." According to the report, over 40% of the electricity use in developing countries is by electric motors in the industrial (including agriculture) sector (U.S. AID, 1988b). One detailed energy analysis in Pakistan identified specific industrial efficiency improvements, including improved controls and lighting, which could reduce industrial energy consumption by more than 20% in 2005 (Miller et al.).

Other recent studies in Kenya and South Korea indicate that efficiency programs have been successful in reducing energy use in heavy industry (Geller, 1986). A detailed analysis of the electricity conservation potential in Brazil indicates that improvements in electric motors and motor controls could reduce industrial electricity consumption by an amount equivalent to 8.7 Gw of new generating capacity (Geller, 1984). Many of the potential industrial energy savings in developing countries are undoubtedly not yet identified because of the relatively little attention that has been given to this issue in the past. However, the fragmentary evidence currently available suggests that these opportunities are much greater in percentage terms than those in industrialized countries and are much cheaper than the incremental cost of increasing energy consumption.

Agricultural Energy Use

On a global scale, agriculture accounts for a small part of "commercial" (excluding traditional biomass) energy use--about 3.5% in 1972-73. However, the percentage in some developing countries may be higher. In addition, the projected transition in developing countries from traditional labor-intensive agricultural practices to modern mechanized practices is expected to increase the use of commercial energy in agriculture significantly in developing countries by the year 2000 (FAO, 1981).

A major goal of most developing countries is to increase productivity in agricultural production either for domestic consumption or for export purposes. If energy conservation is viewed as a constraint to such improvements, it generally will not be viewed as a more important objective. However, productivity increases may be possible through several alternative approaches, with markedly different implications for energy and employment.

Many developing countries are interested in holding down imports of fossil fuels. They may also experience widespread unemployment or underemployment and may seek modernization without displacement of employment. It is important that agricultural modernization be incorporated into an overall development strategy appropriate to each individual country. In this context, energy savings may be achieved in conjunction with other objectives. Goldemberg et al. (1988) point out that some agricultural modernization can occur without such large increases in commercial energy consumption (and associated reductions in labor requirements). Using one type of rice production as an example, they illustrate that many benefits of the "green revolution" in increasing yields per hectare can be achieved with intermediate approaches that do not go as far in substituting mechanical energy for labor.

Expanded agricultural energy needs can also present an attractive opportunity for biomass energy development. FAO (1981) projected that an increase of 17 PJ of oil-equivalent agricultural energy use would be required to double food production in developing countries by 2000. Goldemberg et al. (1988) calculate that this amount of energy in the form of methanol could be produced by thermochemical processes from 40% of the present organic wastes (crop residues, animal manure, and food-processing wastes) in developing countries. Alternatively, feedstocks could come from tree plantations representing land equivalent to 3% of current forest land in developing countries. Other possible areas for efficiency improvements include electromechanical pumping of water for irrigation, more efficient use of existing water resources, and the use of alternative energy supplies such as wind for pumping.

Near-Term Technical Options: Soviet Bloc Countries

In the Soviet Union and Eastern Europe, industrial energy use accounts for nearly fifty percent of secondary energy use. As a share of primary energy equivalent (with electricity conversion losses allocated to end uses of electricity) it is even larger (Mintzer, 1988). These countries have very high energy consumption per unit of GNP. One recent analysis indicates that the current energy intensity of the Soviet economy is "akin to the IEA energy economies of the early 1970s," as shown in Table 7-6 (IEA, 1988). In fact, while energy intensity in OECD countries was declining by over 20% from 1973 to 1986, energy intensity in the USSR actually increased slightly. Industrial energy conservation could, therefore, provide significant improvement in these countries.

A closer look at some specific industries verifies the general impression of energy-inefficiency. The USSR is by far the world's largest producer of steel (WRI and IIED, 1988). Unfortunately, it is also apparently close to last in the world in efficiency. Estimates for 1983 indicate that the USSR used 31 GJ to produce a ton of steel as compared to the Japanese standard of about 19 GJ

TABLE 7-6

Energy Intensities of Selected Economies
(energy/unit of Gross Domestic Product)

	1973	1986
Canada	0.88	0.76
United States	0.76	0.57
IEA Pacific	0.42	0.31
IEA Europe	0.40	0.34
IEA Total	0.56	0.44
Soviet Union	0.99	1.03

Sources: IEA, 1988.

(Chandler, 1986). As shown in Table 7-7, the Soviet Union and many Eastern European countries continue to produce a large percentage of their steel in very inefficient "open hearth" furnaces, which have been virtually eliminated in the OECD. They also do very little recycling, as indicated by the small percentage of steel produced in electric arc furnaces.

One analyst has suggested that Soviet industry has shown some success in improving efficiency with existing technology in their heavy industry (e.g., "housekeeping" measures, refinements of existing technologies), but have failed to assimilate distinctly different, and inherently less energy-intensive technologies. An example is the cement industry, a heavy energy-using sector for which energy use can be greatly reduced by switching from the wet process to a newer dry calcining process. Although the dry process is available in the Soviet Union, it has not been widely utilized (Hewitt, 1984).

There are several reasons for the extraordinarily high energy intensity of Eastern Bloc industry. The Soviet Union (and to a lesser extent Eastern Europe) has enormous energy resources and has historically invested heavily in energy development due to national economic policy rather than demand. Hence, scarcity of energy resources has not provided an incentive to conserve. In addition, the "mark-up" pricing systems used in these countries does not provide a strong incentive for efficiency improvements. In fact, it has been argued that the reward system has actually provided managers with an incentive to consume more energy (Chandler, 1986).

More recently, the value of energy efficiency has been recognized by Soviet leadership. As described by Soviet energy analysts, "the energy economy of the Soviet Union is entering a new period of development. The most economical and favorable located oil and gas resources...are gradually running out." The result is that development of new energy resources is much more expensive and difficult than in the past (Makarov, et al., 1987). One result of rising costs of energy

TABLE 7-7

Innovation in Steel Production Technology
Selected Countries, 1985

Country	Economy Type	"Inefficient" Open Hearth (% of production)	"Recycling" Electric Arc (% of production)
Spain	M	0	61
Italy	M	0	53
South Korea	M	0	31
United Kingdom	M	0	29
Japan	M	0	29
West Germany	M	0	19
Brazil	M	4	25
United States	M	7	33
Romania	C	29	22
China [a]	C	31	19
Yugoslavia	C	34	26
India [a]	C	42	19
Poland	C	42	15
East Germany	C	34	31
Hungary [a]	C	51	13
Soviet Union	C	57	11

M = Market-oriented; C = Centrally planned.

[a] Though this country's agricultural economy is market-oriented, its industry is not.

Source: Chandler, 1986.

development has been the explicit inclusion of energy efficiency measures in central economic and energy planning. Targets have been set that would result in more than a 20% reduction in the energy intensity of the Soviet economy (Makarov, et al., 1987).

The Soviet Union has historically done very well in the utilization of industrial waste heat for electricity generation (cogeneration) and for other heat needs, such as district heating. This trend is continuing. In the Leningrad region, for example, the 1981-1990 energy plan calls for savings of about 2 EJ of previously-projected industrial energy use through a combination of improved industrial technology and expanded use of waste heat for both electricity and other heat needs (Glebov and Kovlenko, 1987).

In addition to efficiency improvements, other options for reducing greenhouse gas emissions from industry in the Eastern Bloc are possible through fuel switching. Although the major resources are generally located far from current industrial centers, the Soviet Union has the world's largest proven recoverable natural gas reserves in the world, amounting to about 39% of the World total (IEA, 1988). In addition, its undeveloped geothermal and hydroelectric resources are significant (as discussed in **PART TWO: ENERGY SUPPLY**). It would be technically possible, therefore, for the USSR to substitute various alternative fuels for current and projected coal use in the industrial sector, although the costs of such substitution have not been well analyzed.

Summary of Near-Term Technical Potential in the Industrial Sector

Some available projections based on trends in structural change and process technology improvement alone suggest that industrial energy use in the OECD countries may not rise significantly over the next 25-40 years (Williams et al., 1987). The No Response scenarios used in this study are consistent with this view, showing roughly constant to slightly increasing industrial energy use for industrialized countries through 2025. Very recent data for 1987 and 1988 in the U.S. show sharp increases in durable goods and basic material production (U.S. DOC, 1988). If these very recent trends continue, industrial energy use in OECD countries would be higher than indicated in the No Response scenarios. Industrial energy consumption in the East Bloc and developing countries increases substantially in the No Response scenarios.

The technical options identified above could reduce industrial energy consumption by 25% below the levels in the No Response scenarios in the 2000-2010 time frame. One recent analysis indicates that cost-effective conservation could result in an absolute decline of about 19% in industrial energy consumption (fuel and purchased electricity) in the U.S. by the year 2010 (Ross, 1988). Changes incorporated into the Stabilizing Policy cases in this document result in small reductions in the U.S. and industrialized countries. These scenarios appear to be well within the cost-effective technical potential; the achievability of these targets within real-world policy constraints is addressed in **CHAPTER VIII**.

Long-Term Potential in the Industrial Sector

Over the long term, technological options for improving efficiency in industrial energy use are very speculative. Several concepts have been advanced by various analysts that may warrant further study to identify potential options for reducing long-term industrial demand for fossil fuels.

Structural Shifts

As discussed above, over the long term, shifts in the structural composition of industrial activity will undoubtedly continue, with significant energy consequences. As discussed by Ross et al. (1987), production of basic (and inherently energy-intensive) materials has tended to decline over time as a share of GNP after an economy achieves a certain level of affluence. Three components of this shift are:

- Substitution of new (and often less energy-intensive) materials;
- Product and production design changes that result in more efficient materials use; and
- Saturation of major markets for material-intensive products, including infrastructure and material-intensive consumer products.

These effects can be expected to continue in the future and to some degree are incorporated in all the scenarios of future energy use presented in this report. With combinations of policies, such as economic incentives and aggressive research and development, these effects can be accelerated considerably, especially in the developing countries where major increases in industrial energy use are expected. It is currently very difficult to identify, much less quantify, the effects of actions to achieve the technical potential. Further study of long-term trends in the structure of industrial activity and specific policy options for influencing these trends is needed.

Advanced Process Technologies

As pointed out by Ross (1985), major reductions in energy intensity in industrial processes can come about through "revolutionary" change in process technology. Typically, process change is not motivated primarily by energy conservation, but large reductions in energy intensity often result due to technological advances. An example is advanced technology for steel production now under development that could result in very large energy savings per unit of output. About 40% of the energy used in iron and steel production is related to shaping and treating starting with liquid steel. Advanced processes utilize controlled solidification, perhaps very rapid, of thin castings near their final shape. When fully developed, this technology should eliminate almost all of the energy use currently associated with rolling and shaping (Ross, 1985).

In the petrochemical industry research is currently underway to identify advanced separation techniques that could eliminate many of the losses inherent in the current distillation process. Gas separation membranes, gas adsorption and liquid mass separating agents are all currently commercial for very specialized petrochemical applications and use considerably less energy than the distillation processes they have replaced (Mix, 1987). Over the long term, wider applications of these or similar technologies may further reduce process energy requirements.

In general, advanced technologies are attractive because of lower total cost, better quality control, reduction in inventories, greater flexibility, etc. as well as improved energy efficiency. It is difficult to identify possible process technology improvements that could become available through research and development over the long term, although it is likely that energy efficiency improvements will be part of these developments.

Another long term area of process technology advancement is the use of biological phenomena in production processes. Although it is difficult to even identify specific applications of biological processes at this time, they appear to offer possible improvements in speed, control, and precision of process technologies (Berg, 1988). As such technologies emerge, they will undoubtedly offer additional opportunities for reductions in fossil energy use. Industrial policies designed to stimulate technological advances and capital turnover will ultimately also lead to reduced energy requirements.

Non-fossil Energy

Although it is likely that energy intensity of industrial activity will continue to decline over the long term, significant levels of energy consumption will no doubt still be required. Opportunities exist for meeting these demands with non-fossil energy sources. Many industrial technology experts (see, for example, Berg, 1988, Schmidt, 1987) have suggested that increasing use of electricity in industrial processes over the long run is likely because of its superior characteristics of controllability and minimal loss or error.

Even though production of electricity involves large losses, this is often offset because the more sophisticated and precise production processes it allows are generally less energy-intensive at the end use. Increasing electrification of industrial processes at the end-use point allows for a wide variety of alternative generation options (as discussed in **PART TWO: ENERGY SUPPLY**), which can reduce greenhouse gas emissions.

In addition, one analyst has suggested that economic competition will cause energy-intensive industries over the long run to locate geographically where isolated resources of cheap and hard-to-transport energy are available. Examples cited include natural gas and hydro locations in Canada, Brazilian hydropower sites, and natural gas locations in the Middle East (Ross, 1985). The same logic could also apply to locations with geothermal and solar resources as those technologies become competitive. Policies could be implemented to discourage fossil fuel use (see **CHAPTERS VII and IX**), as well as to encourage movement of heavy industry to locations where renewable resources are economically attractive.

PART TWO: ENERGY SUPPLY

This section discusses technical options for reducing greenhouse gas emissions by (1) utilizing fuels for power generation more efficiently, and (2) altering the types of energy supplies we use. These two goals have one common objective: to supply a similar amount of useful energy services compared to current energy consumption practices, but in such a way that the amount of greenhouse gas emissions are minimized. Options for reducing greenhouse gas emissions in end-use applications, particularly by improving energy efficiency and switching fuels, were discussed in **PART ONE: ENERGY SERVICES**. This section focuses on possible options for improving the delivery of energy services by reducing the losses during energy production and conversion processes. Additionally, the types of energy supplies can be altered by developing sustainable sources of energy that do not emit greenhouse gases.

As discussed in chapters IV and V, fossil fuels currently dominate commercial energy use globally (88 percent of primary energy supplied in 1985). This demand for fossil fuels is expected to continue in the future, e.g., fossil energy production in the No Response scenarios increases by 28-73% by the year 2025 in the Slowly Changing World and Rapidly Changing World scenarios, respectively. Much of this increase in fossil fuel demand will be for electricity generation, with coal as the primary fuel, since it is a relatively inexpensive, abundant resource globally. For example, by 2025 coal use for electricity generation increases by 30% in the SCW scenario and by 130% in the RCW scenario.

In the Stabilizing Policy cases first presented in Chapter V, several measures are assumed to reduce greenhouse gases emissions from the production of electricity. These include improved efficiency in electricity generation, greater use of natural gas to displace coal, recovery of methane from coal seams, and increased use of renewables, e.g., biomass and solar, for producing electricity and synthetic fuels. The contribution that these measures can make to reducing greenhouse gas emissions can be considerable. These options help to reduce the percentage of electric utility primary energy consumption from fossil fuels from over 60% in 1985 to under 40% in 2025 in both the SCWP and RCWP scenarios (see Figure 7-10). The extent to which any specific technological option is emphasized to reduce global warming is a matter for future consideration; as discussed in this section, however, there are many options for altering our current dependence on fossil fuels.

The first part of this section discusses possible options for altering current patterns of fossil fuel use. This is clearly one of the highest near-term priorities, since as discussed in Chapters IV and V, current commercial energy use globally is dominated by fossil fuels. In many cases, however, options exist for reducing emissions from these applications. This is followed by a discussion of possible supply alternatives to fossil fuels, including increased use of biomass, solar resources, additional renewable energy resources, nuclear power, and options for enhancing energy storage and delivery to consumers.

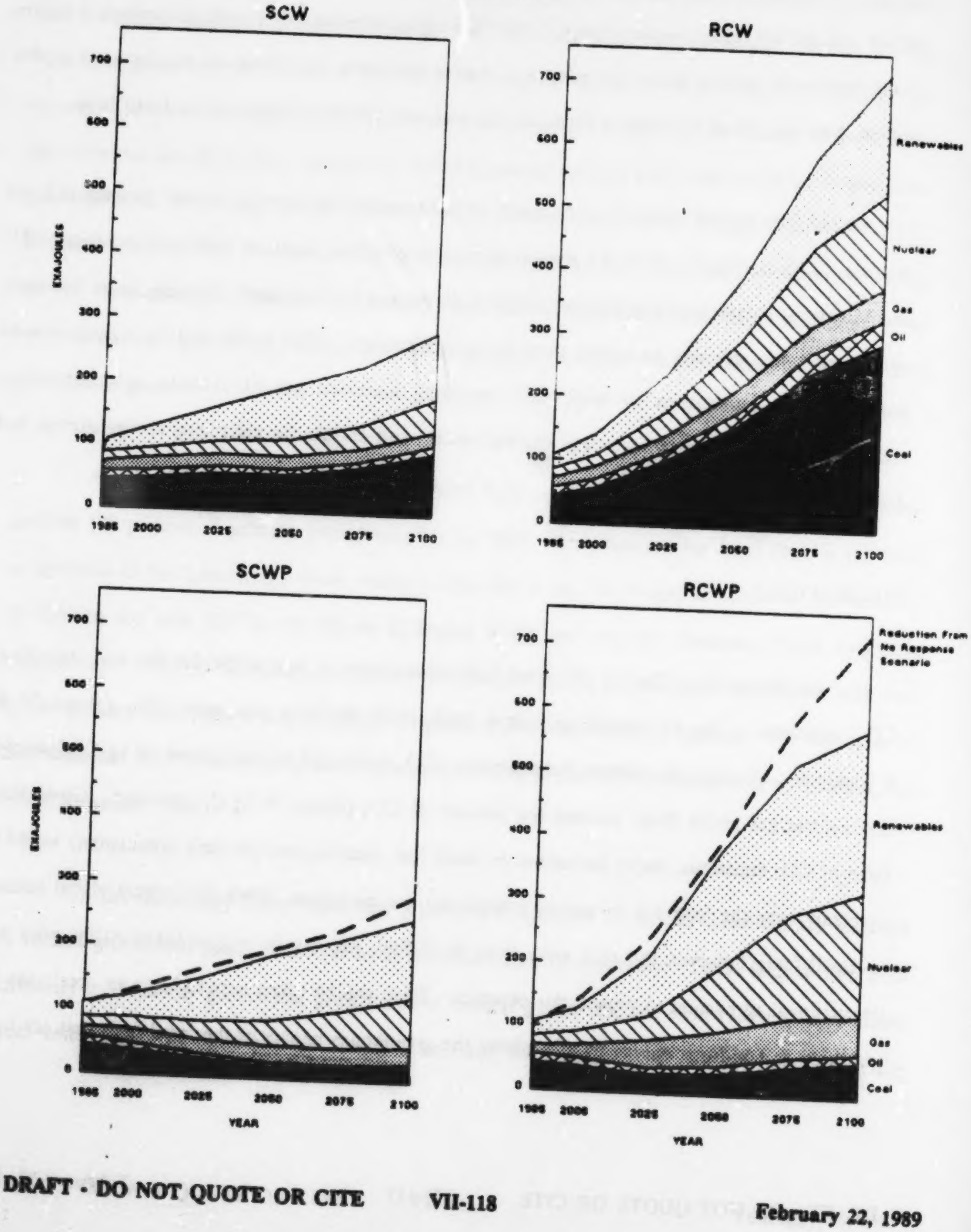
FOSSIL FUELS

As discussed in Chapter IV, fossil fuel consumption is responsible for the vast majority of CO_2 emissions. On an energy-equivalent basis, coal produces the most CO_2 (about 24 kg C/gigajoule), oil about 80 percent the amount of CO_2 compared to coal (about 19 kg C/gigajoule), and natural gas about 55-60 percent the amount of CO_2 (about 14 kg C/gigajoule). Given these rates of CO_2 emissions, major reductions in fossil fuel consumption (or their elimination) would be necessary over the long run to control greenhouse gas emissions. With the current global reliance on fossil fuels, however, the shift away from fossil fuels can not be accomplished easily, even with international agreement to pursue this objective. Steps can be taken now to begin or accelerate the transition to non-fossil energy by minimizing the greenhouse impact of the fossil fuels that are used.

FIGURE 7-10

ELECTRICITY UTILITY DEMAND BY FUEL TYPE

(exajoules)



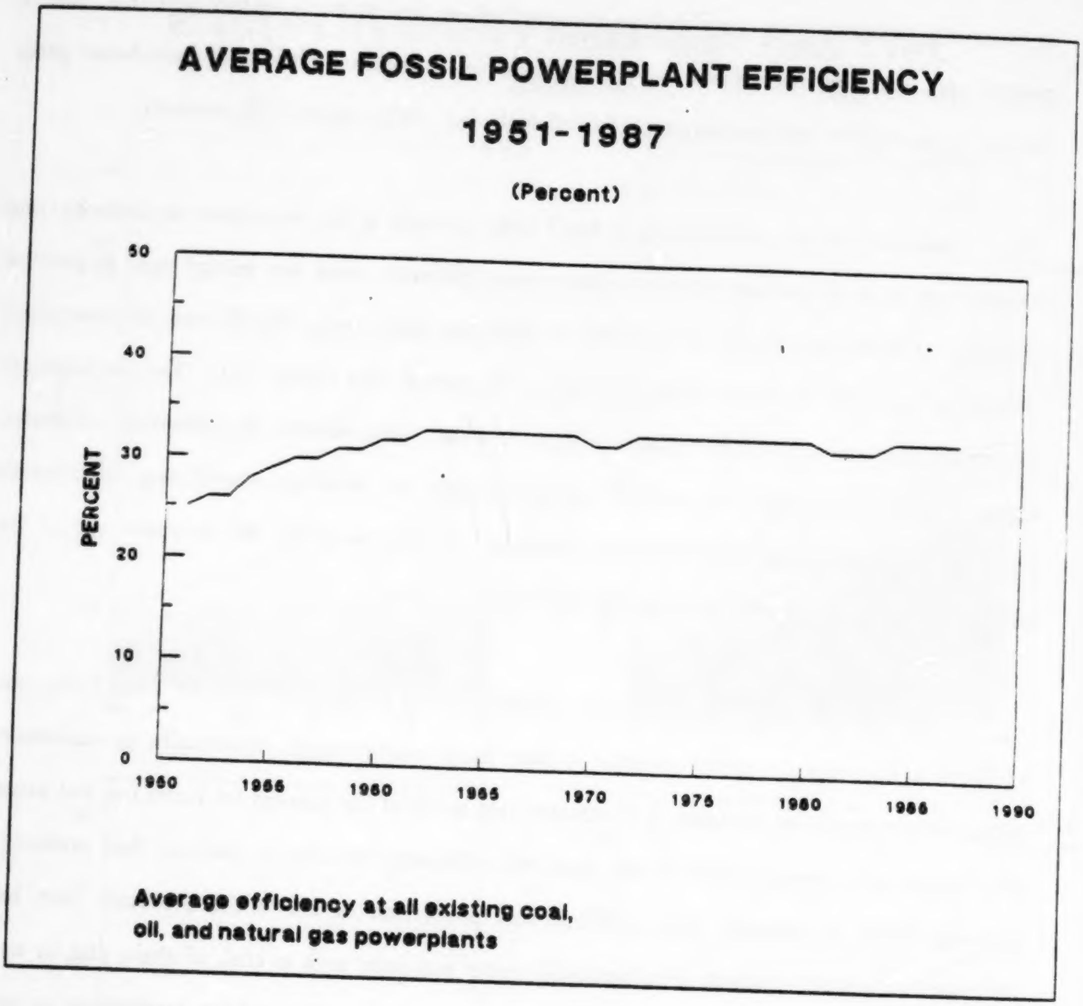
Possible actions include improving the efficiency with which fossil fuels are produced and converted to electricity, switching from more carbon-intensive fuels to less carbon-intensive fuels (e.g., coal to natural gas), and applying various engineering controls to reduce emissions of greenhouse gases during the production and consumption of fossil fuels (e.g., NO_x control, CH_4 recovery).

Since one of the primary uses of fossil fuels currently is the production of electricity, one potential option is to produce electrical power more efficiently, using less energy input to produce electricity. For example, in the U.S. during the 1950s and early 1960s, the efficiency of powerplants consuming fossil fuels increased from 25 to about 32 percent (see Figure 7-11). This improvement has stalled since the early 1960s because of fewer technical improvements in combustion techniques, higher energy consumption by auxiliary equipment used for pollution control (e.g., electrostatic precipitators for particulate removal and scrubbers for SO_2 removal), and increased use of less efficient fuels, such as subbituminous coal and lignite.

Although electricity production is currently one of the primary uses for fossil fuels, other applications have been proposed in order to meet future energy needs. Specifically, as conventional petroleum resources are depleted, it is expected that much of the demand for liquid (oil and natural gas liquids) and gaseous (natural gas) fuels will ultimately be met by synthetic fuel production. Although there is currently little synthetic fuel production in the world, processes have been developed to convert relatively abundant solid energy resources such as coal, oil shale, and tar sands to liquid or gaseous products that could be consumed in the same end-use applications as more conventional resources.

The production of synthetic fuels, however, typically requires the consumption of significant amounts of energy to produce the liquid or gaseous fuels. These conversion processes produce greenhouse gas emissions, particularly CO_2, so that the total emissions per unit of energy are higher

FIGURE 7-11



AVERAGE FOSSIL POWERPLANT EFFICIENCY

1951-1987

(Percent)

Average efficiency at all existing coal, oil, and natural gas powerplants for synthetic fuels than for conventional fossil fuels. For example, the CO_2 emissions from production and consumption of liquid fuels from coal is about 1.8 times the amount from conventional liquid fuels from crude oil (see Chapter IV for further discussion).

The following sections explore possible options for reducing the greenhouse impact of fossil fuels. Using fossil fuels more efficiently is discussed, including refurbishment of existing powerplants, repowering opportunities (including application of clean coal technologies), and cogeneration. Greater use of natural gas is discussed since it produces less CO_2 than oil or coal. Methods for controlling greenhouse gas emissions are also presented.

Refurbishment of Existing Powerplants

Energy use at existing powerplants can be reduced by refurbishing the plant to keep it operating at optimal efficiency. Over time, these efficiencies decline due to wear and various aging processes. For many economic reasons it has become clear over the past decade that utilities in the U.S. are planning to keep existing powerplants in service longer than initially planned (Democker, et al., 1986). It is likely that this trend will occur globally as well to minimize the need to invest in new powerplants. As these powerplants age, however, declining efficiency will become more widespread than in the past.

In response, the U.S. electric power industry has developed new techniques for extending the life of powerplants. The extent of efficiency improvement depends on how badly the specific plant had degraded and the extensiveness of the upgrades. Increases in efficiency in the range of 3-4% appear to be possible at many existing units, with even greater improvements possible in some cases (PEI 1988).

In developing countries, the opportunities for generating efficiency improvements may be much greater. According to a recent study by U.S. AID (1988b), "The majority of thermal powerplants in developing countries operate at lower-than-design capacity and efficiency." Many of these powerplants use more than 13 MJ[1] of fuel to generate a kWh of electricity, compared to typical design heat rates of 9-11 MJ/kWh. It is estimated that a rigorous program of powerplant rehabilitation could improve overall fuel use efficiency for thermal power generation by 10% or more in most developing countries (U.S. AID, 1988b).

Clean Coal Technologies and Repowering

As new powerplants are constructed to meet increasing electricity needs, many of these plants are likely to be fossil-fueled. To the extent that new powerplants use fossil fuels, greenhouse gas emissions can still be reduced by using the most efficient conversion technologies. The U.S. Department of Energy, the Electric Power Research Institute, and many other organizations have been investing significant funding in research, development, and demonstration of "clean coal technologies" designed to allow burning of coal to generate electricity with maximum efficiency and minimum environmental impact (U.S. DOE, 1987e). These technologies offer the potential to significantly reduce the amount of traditional air pollutants such as sulfur dioxide and nitrogen dioxides. However, they may also affect the amount of greenhouse gas emissions, particularly for those technologies that improve the overall efficiency of converting coal to electricity. For example, some of these technologies can improve efficiency 10-25% relative to conventional coal combustion technologies.

---

[1] 1 MJ = 1 Megajoule = 10^6 joules.

Three of these advanced technologies currently in the demonstration phase are atmospheric fluidized bed combustion (AFBC), pressurized fluidized bed combustion (PFBC), and Integrated Gasification/Combined Cycle (IGCC). AFBC is likely to be very similar in efficiency to conventional technology, and therefore not beneficial in reducing greenhouse gas emissions. The PFBC and IGCC systems, however, are projected to increase conversion efficiencies as much as 10-20%, with corresponding reductions in CO_2 emissions per unit of electricity produced (U.S. DOE, 1987e).

Clean coal technologies can be used for newly-constructed powerplants, but also to "repower" existing powerplants. In repowering, the basic combustion components of existing powerplants are replaced with one of the new technologies. Additionally, new components, such as a gas turbine cycle, may also be installed in combination with some refurbished components of the existing powerplant. The result is a hybrid plant with performance very much like that of an efficient new unit.

Cogeneration

Cogeneration is typically the production of both steam and electricity from the same source, with the steam used to meet heating and process requirements at a facility and the electricity used on-site or sold to electricity customers. Because it is more energy-efficient than conventional generating options, it has been encouraged in the U.S. recently by many regulatory and legislative initiatives. For example, the Public Utilities Regulatory Policy Act (PURPA) encouraged cogeneration by establishing a process ensuring that cogenerators with low production costs could sell this cogenerated electrical power to electric utilities.

As discussed earlier **PART ONE: ENERGY SERVICES**, cogeneration has been very popular with large industrial energy users as one approach for reducing their overall energy costs. Most of the approximately 18 GW of currently-operating cogeneration projects in the U.S. and an additional 29 GW under active development fall into this category (Williams, 1988). Similarly, as electric utilities face more competition from industrial cogenerators and independent power producers (i.e., companies not regulated as utilities but do produce power), they may choose to retrofit some existing generating facilities with cogeneration, using the waste heat from electricity production for district heating or industrial process heat applications. Engineering assessments have shown this potential retrofit option to be economically attractive for powerplants burning coal and located close to steam load centers (Hu, et al., 1984).

Natural Gas Substitution

Natural gas (which is primarily methane) has just over half the carbon per unit of energy as coal. In applications such as electricity production where coal is frequently used, switching to natural gas would substantially decrease CO_2 emissions. As discussed previously in **PART ONE: ENERGY SERVICES**, natural gas is currently used in several key end-use applications, particularly a wide variety of industrial energy applications and in residential and commercial space heating. In addition to its end-use potential, natural gas can be used as a fuel for electricity generation. The discussion below focuses on the technical options and advantages of using natural gas as a fuel for electricity generation, and then reviews the issue of how much natural gas is available overall since its role as an end-use fuel and a fuel for electricity generation depends on the amount of natural gas resources available and the cost at which these resources can be supplied.

Natural Gas Use At Existing Powerplants

There are several near-term alternatives for increasing the use of natural gas for electricity generation. One relatively inexpensive option would be to increase the utilization of existing natural gas and oil-fired (most of which can also consume natural gas) powerplants. For example, in 1987 average capacity utilization rates for U.S. oil and gas powerplants were 40% relative to 58% for coal powerplants. Thus, there is some technical potential to increase gas use by increasing the utilization of natural gas-fired powerplants. However, these plants are utilized less because the variable cost of power is higher at most oil and gas plants than at coal, nuclear, and hydro powerplants and oil and gas-fired powerplants can be switched on and off more easily and with less wear on the systems to meet rapid increases in electricity demand. Since electric utilities produce electricity with their least expensive powerplant, policies would have to be adopted to increase utilization of natural gas capacity.

Advanced Gas-Fired Combustion Technologies

An additional option for increasing natural gas use is the construction of new gas-fired combined cycle or combustion turbine powerplants. These powerplants cost significantly less to build than coal powerplants and are typically more energy efficient. They could also be part of a near-term solution since the lead times for plant siting and construction average about two to four years versus six to ten years for coal-fired powerplants. These advanced combustion technologies are not in greater use primarily because of investors' expectations that the costs of natural gas over the operating life of the facility would be substantially higher than other fuel alternatives (such as coal). As a result, despite the lower capital costs of these technologies, electric utilities have often invested in other alternatives because total operating costs of combined cycle or combustion turbine technologies have been perceived to be greater than coal-fired powerplants.

Combustion turbines--Simple/Combined Cycle. Combustion turbines are similar to jet aircraft engines in that fuel is burned in compressed air, with the combustion gases then used to turn a turbine for electricity generation. This process is known as a simple cycle turbine. After the hot gases are used to produce electricity, the exhaust gases can be converted to steam, which can be used to generate additional power in a process known as combined cycling. Most combustion turbines in use are simple cycles, which are used primarily for peak power requirements due to their favorable operating characteristics (primarily their ability to increase power production quickly) and low capital costs, although operating costs are high overall. Combined cycle capital costs are higher and more efficient, and hence, are currently preferred for units expected to be utilized more frequently.

Aeroderivative Combustion Turbines. Recent advances in jet engine (aeroderivative) technology, including new materials and designs that enable combustion to occur at higher temperatures, have made turbines more efficient. Many of these advances are being, or could be, applied to turbines for generating electrical power. For example, existing simple and combined cycle systems have efficiencies of about 32% and 42%, respectively, compared to conventional coal powerplants that have efficiencies of about 31-32%. Recent improvements in aeroderivative technology could significantly improve these efficiencies. For example, one technology that has been recently commercialized is the steam-injected gas turbine (STIG). STIG units take any steam not needed for process heat requirements and inject it back into the combustor for added power and efficiency, e.g., in a simple cycle application the efficiency of the turbine might be 33% with an output of 33 MW, while with full steam injection the efficiency would increase to 40% with an output of 51 MW (Williams, 1988). An improvement in steam injection that has been proposed is the intercooled steam-injected gas turbine (ISTIG). ISTIG cools the compressor bleed air used for turbine blade cooling, allowing a much higher turbine inlet temperature. With this technology the single cycle efficiency cited above would increase from 33% to 47% and output from 33 MW to 110 MW; the estimated capital cost of ISTIG is about $400/kW (Williams, 1988).

Natural Gas Resource Limitations

There is a significant amount of research and debate over the quantity of natural gas that is available. As discussed in Chapter IV, global gas resources are estimated to be significantly smaller than global coal resources (resource estimates by the World Energy Conference indicate that coal resources are about 30 times greater than gas resources). Within the U.S. there is disagreement over the size of this difference. One source has indicated that in the U.S. the natural gas resource base is as large as the coal resource base when one compares the economically recoverable and usable resources; the supply should be adequate for hundreds of years (Hay et al., 1988). On the other hand, based on 1985 consumption levels of about 18.6 EJ, the U.S. DOE has estimated that technically-recoverable U.S. gas resources would last only about 70 years and only about 45 years if limited to supplies that could be marketed for about a maximum of $5/GJ (see Table 7-8). In contrast, U.S. coal reserves are estimated to be about 350 times greater than 1985 U.S. consumption levels (U.S. DOE 1985; U.S. DOE 1986).

In addition to the potential limit on gas supplies, there are also questions about the cost of additional gas supplies, the location of supplies vis-à-vis the areas of demand, the cost of improved distribution systems, and in the case of international trade in liquified natural gas (LNG), the costs of liquefaction, transportation, and regasification facilities.

These concerns over the cost and availability of natural gas may appear unwarranted given the existence of excess capacity and falling prices in the U.S. gas industry in recent years. However, these market conditions may be temporary. Current excess capacity follows a period in the 1970s when natural gas was in short supply. The recent changes are primarily due to natural gas price deregulation, which allowed prices to increase from previously controlled levels. The price increases had two effects: (1) a decrease in demand as prices increased, and (2) an increase in supplies as the

TABLE 7-8

Total U.S. Gas Reserves And Resources (Exajoules)

	Technically Recoverable Gas[a]	Recoverable Gas By Price[b]	
		<$3/Mcf	$3-5/Mcf
Lower 48 (Conventional)			
Proved Reserved, 12/31/86, Onshore and Offshore	171	171	---
Inferred Reserves/Probable Resources, 12/31/86, Onshore	91	91	---
Inferred Reserved, 12/31/86, Offshore	25	25	---
Extended Reserve Growth in Nonassociated Fields, Onshore	128	60	19
Gas Resources Associated with Oil Reserve Growth[c]	66	32	12
Undiscovered Onshore Resources	236	95	63
Undiscovered Offshore Resources[d]	144	58	30
Subtotal	860	533	125
Lower 48 (Unconventional)			
Gas in Low-Permeability Reservoirs	194	75	53
Coalbed methane	52	9	4
Shale Gas	33	11	5
Subtotal	279	95	63
Alaska			
Reserves			
Inferred Reserved (Cook Inlet Area)	36	8	0
Undiscovered, Onshore and Offshore	3	3	0
	100	2	2
Subtotal	139	13	2
Total	1,278	640	189

[a] Volumes of gas judged recoverable with existing technology.

[b] Volumes of gas judged recoverable with existing technology at wellhead prices shown (1987$). Mcf represents one thousand cubic feet (about 1.1 GJ), which is a common measure of gas quantity.

[c] Judged at oil prices of <$24/bbl and $24-40/bbl.

[d] Outer Continental Shelf

Source: U.S. DOE 1988.

higher prices of gas prompted increased exploration and development. The duration of the current black market conditions is a matter of much debate, but as the demand and supply for natural gas come into balance, natural gas may no longer be available at current prices.

The relevance of these concerns is not that natural gas cannot play a role in reducing CO_2 emissions; unquestionably, it can. However, the ability of natural gas to replace higher carbon content fuels is a function of the quantity of natural gas available and the cost at which natural gas can be supplied to consumers. That is, even if natural gas is available, its ability to replace other fuels will depend on its cost relative to alternative fuels. Any policies promoting increased use of natural gas need to recognize these factors.

Electric Utility Gas Consumption. In 1985, gas consumption by U.S. electric utilities was about one-fifth of total U.S. gas use, or about 3 EJ. Even though U.S. utilities consume only a minor fraction of natural gas, they can have a large impact on prices because they are frequently the marginal buyer. That is, utilities often have alternative generation options such as oil or coal and can easily switch, unlike many residential or commercial gas users who do not have such flexibility. Increases in electric utility demand for natural gas would affect residential, commercial, and industrial customers by raising gas prices. For example, assuming 13 EJ of consumption, a $1/gigajoule price increase would increase natural gas costs $13 billion per year among all consumers.

To replace a significant amount of electric utility coal consumption would require a very large increase in natural gas consumption. For example, compared to 1985 utility gas consumption of 3 EJ, utility coal consumption was about 15 EJ. Thus, to replace 40% of coal consumption (6 EJ), a 200% increase in utility gas consumption would be necessary, raising U.S. electric utility gas use to unprecedented levels. As a result, any policy to increase natural gas use needs to recognize possible impacts on gas supply and the market price of gas.

Additional Gas Resources

This section discusses two other sources for increasing the available supply of gas to consumers: (1) methane emissions during the production and distribution of natural gas, and (2) methane recovery from coal seams. In each of these cases, increasing the amount of methane available to consumers would often have other positive environmental benefits by reducing the amount of CH_4 and CO_2 emitted to the atmosphere.

Emissions from Natural Gas Flaring, Venting, and Leaking. As discussed in Chapter IV, during the production of oil and natural gas, natural gas[2] may be vented to the atmosphere as CH_4 or flared (producing CO_2). Additional CH_4 emissions are also produced during the refining, transmission, and distribution of natural gas. These emissions can be reduced through more careful production and maintenance procedures or by capturing the gas for on-site use or sale to gas customers.

Gas vented or flared in the U.S. represents around 0.5% of annual domestic production, while gas losses during transmission and distribution represent less than 2% of production. These values are estimated to be much lower than the global average due to a number of factors, including regulations prohibiting the flaring and venting of gas in the U.S. and the existence of a market and infrastructure to transport and sell the gas. In areas in the U.S. where no market for the gas exists (e.g., Alaska), gas produced during oil production activities is reinjected into the reservoirs in order to maintain pressure. Opportunities do exist in the U.S. for reducing gas losses during transmission and distribution and through maintenance and replacement of old, outdated distribution lines.

---

[2] Natural gas is mostly methane, but the methane content can vary from less than 70% to nearly 100% depending on the source of the gas. We refer to the vented or flared gases as methane, although other trace gases may also be present.

Globally, a larger percentage of natural gas is vented or flared due to fewer regulations governing these releases and a less-developed infrastructure for utilizing the gas. The quantities of gas vented or flared could be reduced through development of an infrastructure to market the gas or through regulations governing these releases.

Coalbed Methane. As discussed in Chapter IV, during coal mining, particularly underground mining, methane trapped in the coal seam is released. Historically, coalbed methane has been viewed as a safety problem during coal mining since methane can accumulate in the coal mine and explode. In the U.S., mining regulations require that underground coal mines be adequately ventilated to prevent this problem. Recently, however, there has been a growing interest in utilizing coalbed methane as a natural gas resource.

Methane extraction from coalbeds, which is being done commercially in a few areas in the U.S., differs from traditional natural gas production in several respects. Perhaps most importantly, the gas production profile differs from conventional gas wells in that maximum output generally occurs two to three years after the wells are in place, compared to immediately afterwards for conventional wells. For a given production site, more wells are drilled to maximize methane flow. Also, because these wells are drilled into available coal seams, they are generally quite shallow (i.e., not more than 3000-4000 feet below ground). While the relatively shallow access helps to reduce drilling costs, more groundwater is encountered, requiring additional efforts to combat this problem.

Due to the relatively new state of the coalbed methane recovery industry, it is difficult to quantify the potential size of this resource. In addition to offering another gas source, coalbed methane recovery could potentially be used to remove methane prior to mining the coal seam. Such recovery would help to ease the problem of methane buildup in coal mines (possibly reducing coal mining costs) and avoid the emissions of CH_4 to the atmosphere that result from current coal-mining operations.

Emission Controls

One technological option for reducing the amount of greenhouse gas emissions is the use of emission control techniques on combustion technologies that generate these emissions. NO_x and CO_2 emission control options for stationary combustion sources, such as electric utility powerplants, are discussed below.

NO$_x$ Controls

Nitrogen oxides (NO_x) are formed during combustion primarily by the combination at high temperatures of nitrogen (N_2) and oxygen (O_2) naturally found in the air and secondarily by the nitrogen that is found in fuels such as coal and oil. Of these two factors, it is the combustion temperature that is the most critical factor affecting the NO_x emission rate. There are a number of currently-available methods for controlling NO_x emissions (based on NAPAP, 1987):

- Low Excess Air (LEA), Overfire Air. These two combustion techniques alter the flow of air during the combustion process. With low excess air the amount of excess combustion air is reduced, thereby lowering emissions up to 15%. With overfire air, some combustion air is redirected to a region above the burners, which can reduce emissions by 30%. Potential drawbacks are incomplete combustion of the fuel, increased smoke, and the extensive plant modifications that may be required.

- Low NO_x burners. This control technique operates within the furnace to limit the mixing of coal and combustion air to create a low-temperature combustion zone. Removal efficiencies approach 45-60%. This technique can be applied to existing and new units, although experience on existing units is quite limited.

- Air and Fuel Staging. When combined, these two controls can achieve 80% removal efficiencies. With air staging, up to 50% of the combustion air is directed above low-NO_x burners. With fuel staging (also known as reburning) additional fuel is burned in a region above the burners to create a fuel-rich combustion zone. Within this zone NO_x is destroyed by reducing conditions that convert NO_x to molecular nitrogen. This technique has been used in full-scale applications abroad, but only in pilot-scale facilities in the U.S.

- Selective Catalytic Reduction (SCR). SCR is a post-combustion control technology that uses a catalyst to reduce NO_x; reductions of 50-80% are possible. Its advantages include relatively simple equipment, no byproduct, and minimal efficiency loss. Its cost-effectiveness, however, depends on catalyst lifetime, which depends primarily on fuel characteristics. SCR has been used abroad, particularly in Japan and West Germany.

CO_2 Controls

Technologies have been developed to remove carbon dioxide from powerplant flue gases and dispose of it in a manner that prevents it from reaching the atmosphere. However, these technologies are unproven and very costly at this time. In one process, carbon dioxide in the flue gas is mixed with water in a solvent solution at temperatures slightly above ambient conditions. The carbon dioxide binds to the reagent and passes to a regenerator chamber where temperatures are elevated. The reverse reaction occurs and carbon dioxide is released, removed, pressurized, and liquified. The reagent is regenerated and reused. The liquid carbon dioxide could then be used for various commercial applications, or pumped to deep ocean locations, deep wells, or salt domes for permanent disposal.

In order to understand the relative costs of this CO_2 removal process, the costs of this system are compared to a conventional sulfur dioxide scrubber in Table 7-9. The carbon dioxide scrubber is 250-350% more costly than the sulfur dioxide scrubber and increases electric power costs 60-80%. The cost of transporting and disposing of the large volume of removed CO_2 has not been adequately assessed, but is likely to substantially increase this estimate. Although some CO_2 could be used for enhanced oil recovery or stored in exhausted oil and gas wells, large-scale disposal would most likely have to be in the ocean. This raises serious environmental concerns that have not been examined.

Emerging Electricity Generation Technologies

There are a number of technological options that could be available in the longer term that would substantially alter the way fossil fuels are utilized. Two of the most-discussed options--fuels cells and magnetohydrodynamics--are discussed below.

Fuel cells

Fuel cells are a new set of technologies now in use in the U.S. space program and expected to eventually be commercially available to the electric power industry. The technology converts fuel energy to electricity using an electrochemical process similar to that employed in chemical batteries.

TABLE 7-9

CO_2 Scrubber Costs Compared To SO_2 Scrubber Costs[a]

	CO_2 Scrubber[b]	SO_2 Scrubber[c]
Capital Cost ($/kw)[d]		
Scrubber	810	220
Pipeline/Disposal	80-710	NA
Variable Operation and Maintenance Costs (mills/kwh)	NA	3.5
Energy Penalty (%)	25	4.5
Capacity Penalty (%)	22	2.5
Fixed Operation and Maintenance Costs ($/kwyr)	NA	10
Total Cost (mills/kwh)[e]	36-47	10.7

---

[a] 90 percent removal of both CO_2 and SO_2.

[b] Steinberg, Cherg, Horn, 1984

[c] 1987 EPA Interim Acid Rain Base Case Estimates.

[d] Greenfield Site.

[e] 65 percent capacity factor; 9 percent capital charge rate; incremental power costs 65 mills per kilowatt-hour; new plant costs of $1,200/kw; fixed O&M for CO_2 scrubber is assumed to be ten dollars per kilowatt-year for comparison purposes only, actual costs could well be higher; 1988 dollars assumed to be worth 42 percent less than 1980 dollars.

Total fuel cell plants may achieve efficiencies of up to 85%. There are several drawbacks to the technology at this time, especially: (1) special fuel requirements, and (2) relatively low reliability.

The fuel cell closest to commercialization is the Phosphoric Acid Fuel Cell (PAFC). This fuel cell converts hydrogen into electricity and water. The hydrogen must be produced, however; considering the conversion losses, overall powerplant efficiencies for large fuel cell plants (e.g., several MW) approach 45%. In theory, the chemical reaction could continue as long as fuel is supplied, but in practice the materials fail after prolonged operation. The current goal is 40,000 hours which, even if achieved, is still well below that of conventional powerplants. Another drawback is that the production of hydrogen from fossil fuels creates CO_2. The section on hydrogen at the end of the chapter discusses this further.

The use of hydrogen in fuel cells suggests the possibility of coupling fuel cells with renewable energy sources. For example, solar powerplants could use any power not delivered to customers to create hydrogen, which could then be used when solar powerplants are not operating or when demand exceeds solar capacity.

Magnetohydrodynamics (MHD)

Magnetohydrodynamics (MHD) is an advanced, efficient generation technology that could use coal as a fuel. In a MHD system, coal is burned at very high temperatures and the hot combustion gases are chemically treated. The gases then pass through a magnetic field created using superconductors, thereby generating power. The gases can also be used in a steam cycle to produce additional power. The MHD system is expected to eventually achieve efficiencies of 60%. In comparison, conventional coal powerplants operate at about 31-32% efficiencies and advanced pressurized fluidized bed combustion (PFBC) and Integrated Gasification/Combined Cycle (IGCC) coal units, now being demonstrated, are expected to achieve 35-37% efficiency.

There are several drawbacks to the MHD technology. It is very capital-intensive, requires superconductors that have only reached the laboratory stage of development, and the high temperature combustion could result in high nitrogen oxide emission rates. Nonetheless, many observers believe MHD systems will eventually be available as these obstacles are overcome, creating an option for very efficient coal combustion.

BIOMASS

Biomass in one form or another continues to be the predominant source of energy for at least half of the world's population. In many countries, such as Nepal, Ethiopia, and Guatemala, over 90% of total energy used comes from biomass (Goldemberg, et al., 1988). Although on a global basis it accounts for only one-seventh of all energy consumed, for over 2 billion people it is close to being the only source of energy.

A number of studies have reported on the alarming rate of global deforestation as the current demand for biomass resources far exceeds the natural rate of regeneration (e.g., IUCN 1980, , WRI 1985). It is this difference between growth and use that contributes to net greenhouse gas emissions. Despite this current situation, biomass energy over the long term offers some of the most promising opportunities for displacing large amounts of fossil fuel use.

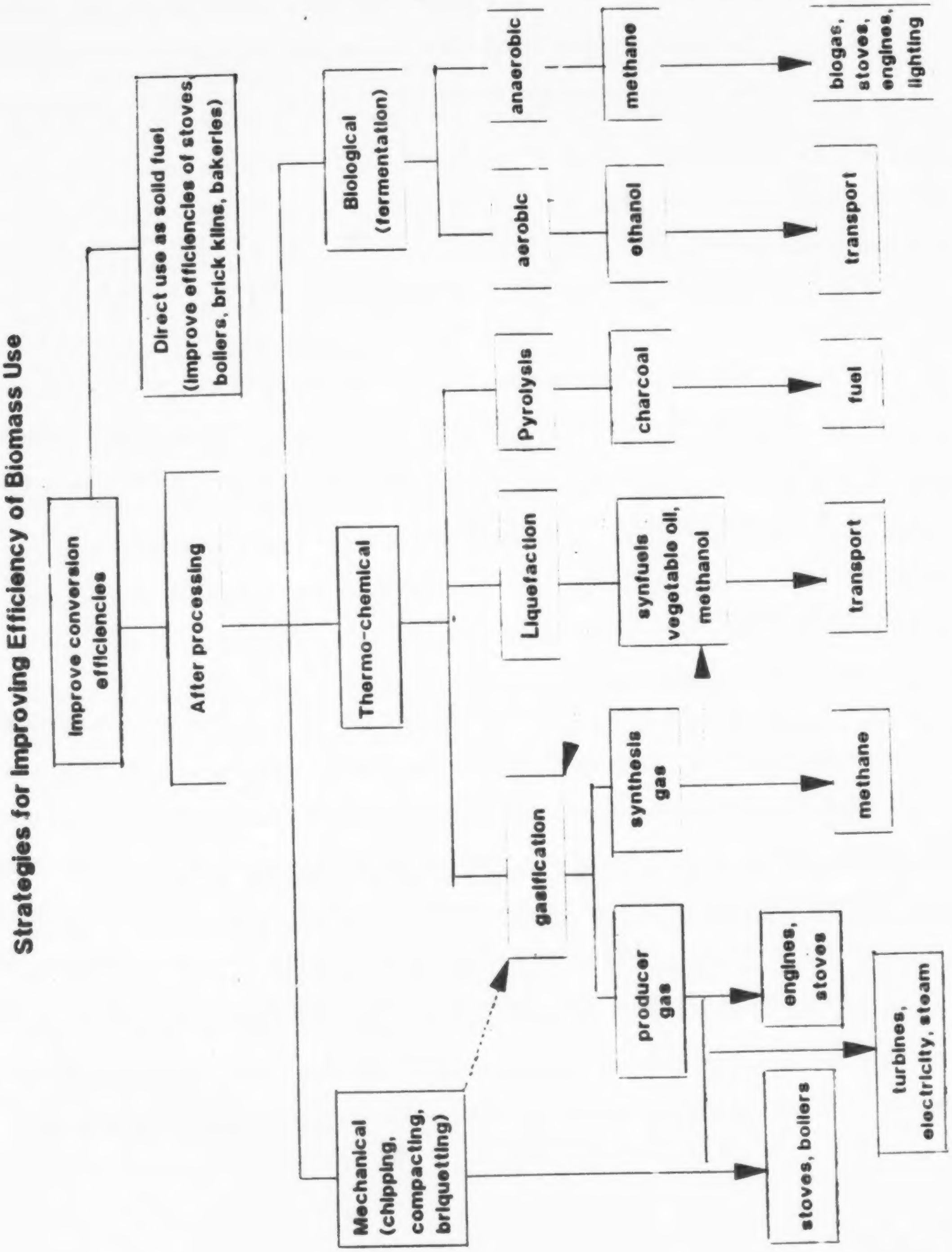
Although biomass fuels account for about 14% of global primary energy use, they deliver a much smaller fraction of useful energy because of the inefficient nature of their current use. However, technologies exist or are under development to provide many times the current level of energy services from the amount of biomass currently consumed globally. In addition, it is also technically possible to greatly increase the annual increment of biomass available for energy use. Methods for increasing supply through agroforestry, biotechnology, etc., and for reducing extractive use of forest products for non-energy purposes are discussed in **PART FOUR: FORESTS**. In this section various approaches are discussed to reduce biofuel demand through fuel switching, by improving end-use efficiencies, and by increasing conversion efficiencies using upgraded fuels (see Figure 7-12).

Direct Firing of Biomass

The primary uses of biomass in direct combustion applications include use in cookstoves, space heaters, bakeries, brick kilns, and boilers of various sizes. Typical conversion efficiencies range from 5-15%. There is tremendous potential for improving the end-use efficiency in each of these energy conversion processes. In fact, this may be the most cost-effective, immediate option for decreasing the demand for biomass resources (e.g., see discussion on technical options for improving efficiency of biomass use in **PART ONE: ENERGY SERVICES**).

Wood or wood products (bark, sawdust, chips, bagasse) are already used directly as a boiler fuel (especially in agroforestry-based industries with readily-available access to wood supplies). But there are a number of modern technologies that can be used to extract much more useful output. Due to the physical variability of biomass (and the lower density of crop residues), very often some improvements in combustion properties can be achieved just by properly sizing the solid biofuels. The energy requirements for sizing and densification must be weighed against improved combustion, convenience, and ease of transport. While this is not absolutely essential when the application is for heating, some amount of sizing and/or briquetting is critical in more efficient boiler or gasifier designs.

FIGURE 7-12


Strategies for Improving Efficiency of Biomass Use
Improve conversion efficiencies
Direct use as solid fuel (improve efficiencies of stoves, boilers, brick kilns, bakeries)
After processing
Biological (fermentation)
anaerobic
methane
biogas, stoves, engines, lighting
aerobic
ethanol
transport
Thermo-chemical
Pyrolysis
charcoal
fuel
Liquefaction
synfuels vegetable oil, methanol
transport
gasification
synthesis gas
methane
producer gas
engines, stoves
turbines, electricity, steam
Mechanical (chipping, compacting, briquetting)
stoves, boilers

Another area in which combustion efficiency can be significantly increased is in the use of advanced burner systems, such as fluidized bed combustors. These use a stream of hot air to suspend the fuel and thus achieve more complete combustion. Some of these technologies can also use certain fuels with high ash or silica content, such as rice husks, that would be harmful to standard combustion systems.

In a few areas, central power stations have been constructed specifically to use wood as a fuel. The facilities that are burning wood for electrical power range in size from 5 to 50 megawatts. Depending on the cost of fuel, conventional wood burning is generally not competitive with conventional fuels due to lower combustion efficiency and greater fuel bulk, which necessitates larger fuel-handling facilities. The localities served by these plants gain various benefits that may offset these inefficiencies. For example, local timber industries may be assisted, and environmental benefits may be obtained from reduced CO_2 emissions.

Charcoal Production

Charcoal is produced by heating wood in the absence of air (also known as pyrolysis). The traditional method of producing charcoal in kilns made of earth, as used for centuries in many regions such as Africa, is very inefficient. Only 15-30% of the energy content of the wood is retained in the charcoal as all of the gases produced during pyrolysis are allowed to escape. Substantial efficiency improvements are possible, e.g., Brazilian kilns built of brick, which produce charcoal for steel manufacture, have achieved overall efficiencies of up to 50%, twice that of traditional methods, by utilizing the gaseous by-products (Miller et al., 1986). Even further improvements are expected (Goldemberg et al., 1987).

Anaerobic Digestion

Anaerobic digestion is a biological process whereby a combustible gas is produced in the absence of oxygen; this gas is a mixture of methane and carbon dioxide similar to the marsh gas produced in swamps and landfills. This technology has the attractive feature of separating the energy content of biomass from its value as a soil conditioner and fertilizer. The energy content is released in a gaseous form (i.e., biogas) that can be utilized at a higher efficiency than the original solid biomass. Biogas is primarily used for cooking and lighting, but can also partially substitute for diesel in engines used for irrigation pumping.

China and India have had extensive biogas programs for more than 15 years (Moulik, 1985). Both programs have concentrated on household systems, with manure and other farm wastes being the most common feedstocks, with over 7 million systems installed, most of these in China. Programs in both countries have had to deal with design, construction, and maintenance problems so that many of the digesters are no longer functioning (Miller, et al., 1986), demonstrating the difficulty of introducing even relatively "simple" low-cost technologies in remote, rural areas of developing countries. Some larger institutional plants have had a higher probability of succeeding than household-size facilities.

Financially, the feasibility of biogas plants depends largely on whether the biogas and biomass residues substitute for fuels or fertilizers that have traditionally been purchased or obtained at zero financial cost. In cases where the biogas or residues do not generate incomes or reduce cash outflows, they are less likely to be viable. However, the nonfinancial benefits of these programs, such as improvements in public health due to lower emissions during cooking or increased mortality of pathogens in the digester, reduced deforestation, less reliance on imported fuels, etc., motivate countries such as China and India to continue subsidies for biogas projects (Gunnerson and Stuckey, 1982).

There are a number of other approaches being tried to make this technology more appealing. Ideally, what is required is a low capital cost technology that permits the use of a wide variety of feedstocks and results in high gas yields over a range of ambient temperatures. In Taiwan, a durable and cheap above-ground bag digester made from bauxite refining wastes has been used with success (Miller et al, 1986). Other promising anaerobic digester designs being explored include the upflow sludge blanket and baffled reactor (Gunnerson and Stuckey, 1982).

Gasification

Many cellulosic materials can be gasified and then either used directly or liquified into methanol. There are two routes for gasifying biomass--one resulting in producer (or wood) gas and the other in higher calorific value synthesis gas. Producer gas is made by heating wood in an almost oxygen-free environment so that the unburned fuel breaks down into gases, ash, and tar. Producer gas was used to propel trucks in World War II when oil was scarce. Synthesis gas is made at higher temperatures with a more pure oxygen source than producer gas, thus eliminating nitrogen, and lends itself to conversion into methanol (see later section on liquid fuels from biomass).

Producer gas can be made using a number of raw materials: wood, charcoal, crop residues, and urban refuse. There are more than 20 companies world-wide selling gasifiers, with Brazil and the Philippines leading in the use of this technology. Gasifiers have been used to power tractors, motor boats, and irrigation pumps and to provide electricity for food processing and other rural needs. They can also replace oil as a boiler fuel.

Electrical Power Applications. Kjellstrom (1985) has shown that for conventional power generation applications, biomass gasifiers compete favorably if the operating times are long, load factors high, and power outputs large. The economics are most favorable for wood-based systems rather than charcoal systems, and could become substantially more attractive if oil prices were to increase or biomass input costs were to decline. One drawback to gasifiers at this time is that current designs do not accept all types of crop residues. Kjellstrom also demonstrated that at 1985 diesel prices it would be uneconomic to run diesel tractors or trucks on producer gas or to use it in industrial applications except for industries with surplus biomass residues. Another technical problem is the need to understand the pollution impacts due to CO emissions and tar condensates from the biomass material.

While there are a number of problems to be resolved before biomass gasifiers can be easily used to replace natural gas in conventional applications, research at Princeton University has shown that integrated gasifier-combustion turbine systems could provide, at small scales (e.g., 5-50 MW), power that is less expensive than power from new hydroelectric, coal, or nuclear plants. (See Box 7-5, Larson, et al., 1987).

Liquid Fuels From Biomass

Biomass can also be used to produce liquid fuels. There are two basic energy types that can be produced with biomass--ethanol and methanol. Each of these fuels is discussed below.

Methanol

Methanol is attractive because current technologies use raw materials grown on lands not required for food production (unlike ethanol). Methanol is produced by producing synthesis gas from

Box 7-5. Biomass-Fired Combustion Turbines

Adaptation of the integrated-gasifier-combustion-turbine technology discussed above (combined cycle or aeroderivative turbines--see **FOSSIL FUELS**) to use biomass presents an attractive option for generating electricity in developing countries (Larson et al., 1987), and could also become important in industrialized countries with advances in biomass plantation productivity (see **FORESTRY**). Indeed, the use of this technology with biomass should be simpler than with coal because biomass is easier to gasify and sulfur removal is unnecessary. The use of aeroderivative turbines (STIG and ISTIG, see **Natural Gas Substitution**) may be particularly attractive because this technology remains quite economic at small scales. While the individual components of such a system have been tested, a commercial demonstration of the integrated package could be very important in increasing investors confidence in this technology.

Biomass-based electricity generation is most economical where the fuel has already been collected for other reasons (e.g., the forest products industry, the cane sugar industry). A prime example is the use of bagasse (i.e., sugarcane residues) at sugar mills and ethanol distilleries. Although these waste products are currently used to provide on-site needs for process steam and often electricity, there has been little interest in increasing efficiency once on-site requirements are satisfied. Indeed, steam and electricity production is often intentionally inefficient because of the desire to consume the wastes. Substituting an ISTIG-based cogeneration system for current steam turbines could increase electrical output by a factor of 20, while still meeting process steam requirements; total system efficiency could exceed 50% (Larson et al., 1987). This could make the cane sugar industry a major electricity producer in developing countries: If this technology were adopted in the 70 sugar-producing countries, total capacity could exceed 50 GW, increasing electricity supplier by 25% in these countries.

Design calculations suggest that the costs would be very competitive with alternatives. Capital costs could be less than $1,000/kW, and electricity could be generated for 3-4 cents/kWh where biomass is available for $2/GJ or less (Larson et al., 1987). (Bagasse in the sugar cane industry is essentially free, implying that the additional costs for producing electricity could be less than 2 cents/kWh.) The barriers to adoption of this technology appear to be primarily institutional -- collaboration between the cane sugar or other biomass producers and the utility industry is required. Furthermore, an integrated biomass-based advanced turbine system needs to be commercially demonstrated, but it is difficult to attract investors for projects considered to entail technological risk in developing countries where this technology is most attractive (see Chapter IX).

biomass, which is then converted to methanol. While the technology for conversion of synthesis gas to methanol is well-established, converting biomass to synthesis gas is a major technical and economic challenge (Williams, 1985). Although this part has been demonstrated (e.g., in West Germany and Brazil), the use of biomass is still not as economic as methanol derived from fossil sources such as natural gas and coal. In the U.S. for wood costing $20/dry ton, the cost of methanol, which burns more efficiently than gasoline, would be $14/GJ, which is equivalent to a gasoline price of $11/GJ (or about $1.50/gallon). As a result, the production of methanol from biomass should be regarded as a promising long-term opportunity if alternative fuel prices rise and/or technical improvements reduce cost. (Williams, 1985).

Ethanol

Biomass can also be used to produce ethanol. Ethanol is useful both as an automotive fuel and as a feedstock for the production of ethylene and other chemicals. Because of certain inherent requirements, as discussed below, its applicability is limited to a few countries. However, to the extent it can replace petroleum products, net emissions of CO_2 will be zero since ethanol from biomass is produced on a renewable basis.

Today, Brazil has the most extensive ethanol development program in the world. The purpose is to provide alternative transportation fuels, based largely on sugarcane-derived ethanol (Sathaye et al., 1988). Although Brazil has succeeded in reducing its oil imports, its program has received mixed reviews, largely because the program has depended on substantial subsidies to ensure its success. Similar efforts in other countries, such as Kenya, have been less successful, usually due to a lack of low-cost biomass or industrial expertise such as that available in Brazil (Miller, et al., 1986). Despite these problems, alcohol production may offer future benefits, as a number of other feedstocks (e.g., grain, sorghum, corn) may provide cheaper ethanol (Brown, 1980) and as technologies to produce ethanol from wood are developed.

Other

One technically-feasible option with biomass-derived liquid fuels is to partially substitute coconut, palm, and other vegetable oils with diesel fuel. These oils can be grown on plantations with high yields, but their worth is usually greater as food than as fuel. The Philippines briefly experimented with a mixture of coconut oil and diesel until changes in relative prices made the approach uneconomical (Miller et al., 1986).

SOLAR ENERGY

Solar energy technologies, as used in this section, refer to technologies that collect, concentrate, and convert solar radiation into useful energy. Technologies for converting solar energy into useable energy offer some of the greatest long-term opportunities for replacing fossil fuels. Within this category, however, there are several types of technologies. Some solar energy applications for the residential and commercial sectors were discussed in **PART ONE: ENERGY SERVICES**. This section will focus on solar thermal and solar photovoltaic options.

Solar thermal systems that are more sophisticated than the residential and commercial systems described earlier are being developed that can concentrate solar radiation to produce higher temperatures. These higher temperatures could be used to make steam, electricity, or power for other industrial process heat applications. The most sophisticated solar conversion approaches are photovoltaic technologies that convert solar radiation directly into electricity. These techniques have received considerable research attention over the last 10-15 years and have progressed considerably as a result. The potential of both photovoltaic and solar thermal technologies, which produce power directly only during daylight hours, will be even greater as more efficient storage technologies increase the cost-effectiveness of storing excess power generated during the daytime for use at other times, as discussed further in **STORAGE TECHNOLOGIES**.

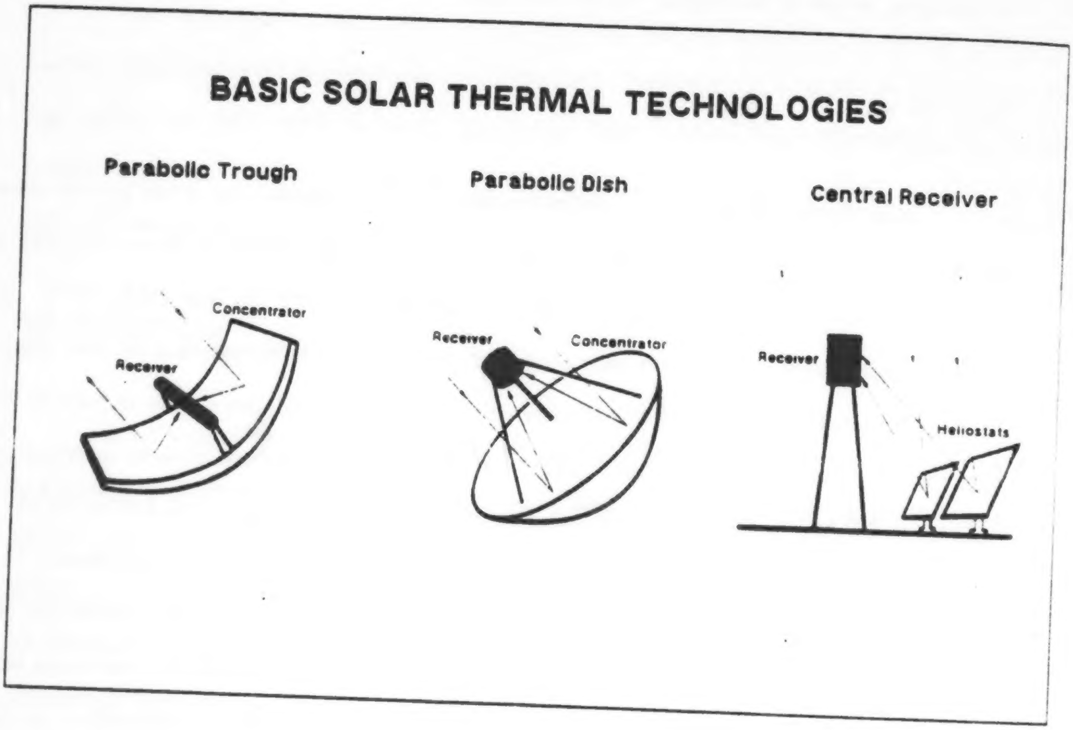
Solar Thermal

Solar thermal technology is a promising area of solar research since it can provide thermal energy at temperatures from 150-1700°C for heat or electricity applications, at almost any scale, and with conversion efficiencies as high as 31.6% for electricity and 80% for heat (IEA, 1987). Solar thermal concentrating systems have been extensively demonstrated in recent years for both industrial heat and electricity generation. 670 MW of electric generating capacity are already in place or under construction in seven countries (Shea. 1988). In the U.S., solar thermal capacity is projected to increase to 550 MW in the next 5 years based on announced industry plans (U.S. DOE, 1987a). The U.S. Department of Energy has estimated recently that a further cost reduction by a factor of 1.5 to 2 would make these technologies competitive with conventional electric generating technologies. DOE has also identified several key technical improvements currently being researched that could achieve the needed cost improvements, leading to economic competitiveness by the mid-1990s (U.S. DOE, 1987a). In recent years most research and development has focused on three thermal technologies--parabolic troughs, parabolic dishes, and central receivers. These technologies, along with solar ponds, are discussed below.

Parabolic Troughs

Parabolic troughs are often referred to as line focus systems because they use one axis only to track the sun; each concentrator (collector) has its own receiver, with parabolic troughs often connected to form a series of collectors (see Figure 7-13). Troughs operate at lower temperatures than most other technologies, e.g., up to 400°C, making them most suitable for industrial process heat

FIGURE 7-13


BASIC SOLAR THERMAL TECHNOLOGIES
Parabolic Trough
Concentrator
Receiver
Parabolic Dish
Receiver
Concentrator
Central Receiver
Receiver
Heliostats

Source: IEA, 1987

applications. The thermal efficiencies of these units have improved significantly in recent years, reaching 65-70%, with availabilities exceeding 95% (IEA, 1987).

Parabolic Dishes

Parabolic dishes differ from troughs in that they are point focus systems, i.e., a two-axis tracking system is employed to follow the sun (see Figure 7-13). The higher concentration ratios allowed by this design (from one hundred to several thousand suns) produces temperatures approaching 1700°C, making electricity conversion possible. This technology currently holds many efficiency records, including the highest conversion efficiency (31.6%). Several of the most ambitious development projects are in the U.S., with installed capacity at some projects approaching 5 MW. DOE estimates total system cost at $3,400/kW, although cost reductions of 40% are considered feasible (IEA 1987).

Central Receivers

Central scale receivers are the largest scale thermal technology. The receiver is typically mounted on a tower surrounded by a large field of nearly flat tracking mirrors called heliostats (see Figure 7-13). The heliostats focus the solar energy on the receiver, achieving working fluid temperatures of 1500°C or higher (IEA 1987). Several countries are studying central receivers, with the largest plant built in southern California (10 MW). This plant has exceeded peak design output by 20%, operated at night from storage, and achieved overall plant efficiency of 13% (IEA 1987). Heliostats account for 40-50% of total costs, and consequently are the focus of most cost reduction efforts; recent developments indicate that cost reductions of 50% could be achieved in one or two years (IEA 1987).

Solar Ponds

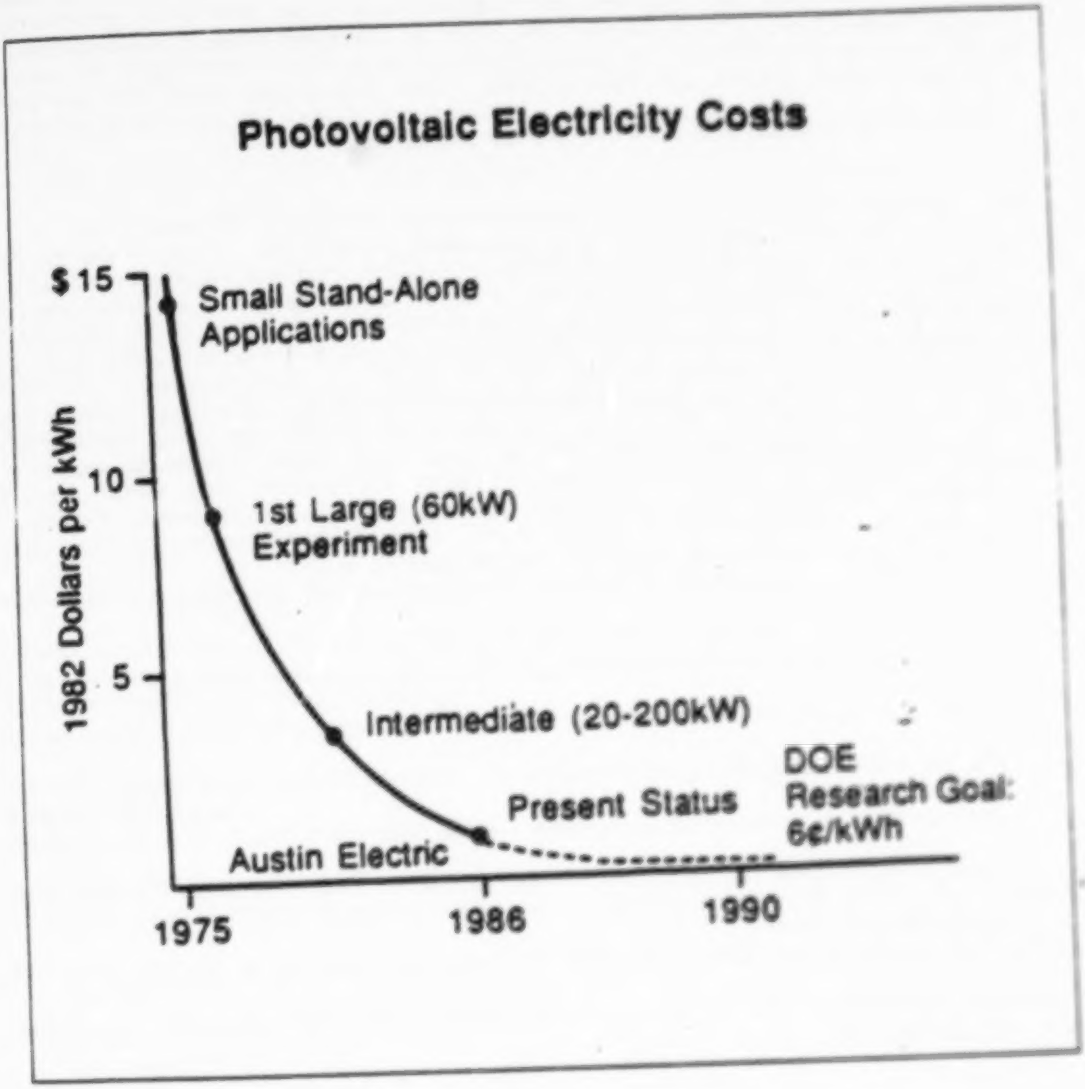
Solar ponds collect and store heat in large bodies of water and operate at much lower temperatures than other solar thermal technologies (85-100°C). In a typical design, a salt gradient below the surface acts as an insulating barrier by trapping incoming solar radiation. Large heat exchangers are used to extract the thermal energy, which can be used for many purposes, including seasonal heat storage for space heating, low temperature process heat applications, or even electricity production. Research into this technology has achieved thermal efficiencies of 15%, with electrical conversion efficiencies of about 1-2% (IEA 1987). Despite these low efficiencies, solar ponds can be attractive since capital costs are very low.

Solar photovoltaic

Solar photovoltaic (PV) technologies convert solar radiation to electricity (DC, or direct current) without moving parts or thermal energy sources. Photovoltaic technology was initially developed in the 1950s; these first systems were about 100 times more expensive than conventional generation technologies, but major improvements have reduced this differential to 3-4 times current energy costs. This differential is even lower when compared to current replacement costs. Figure 7-14 shows the dramatic progress that has been made since 1975 in reducing the costs of electricity from photovoltaic systems.

The principal drawback with photovoltaics is their high capital costs. The current goal is to reduce costs to about 6 cents/kwh (which is comparable to the best conventional powerplant costs), at least for conditions in the southwestern United States where insolation is high. The U.S. DOE is projecting that its cost goal ($0.06/kwh) may be achieved in the 1990s and that photovoltaic systems could provide up to 1.5 GW of generation capacity by 2005 (U.S. DOE, 1987a). Researchers at

FIGURE 7-14


Photovoltaic Electricity Costs
$15
10
5
1982 Dollars per kWh
Small Stand-Alone Applications
1st Large (60kW) Experiment
Intermediate (20-200kW)
Present Status
Austin Electric
DOE Research Goal: 6¢/kWh
1975
1986
1990

Princeton University are also projecting major technological breakthroughs in amorphous silicon solar cell technology. They have projected that capital costs (almost the entire cost for PV) for these cells may decline by over 80% by the year 2000, while the conversion efficiency of photovoltaic arrays roughly doubles (Ogden and Williams, 1988). This could greatly expand the contribution of photovoltaic electricity generation over the next several decades.

The basic principle behind solar photovoltaic power is that as light enters the PV cell, electrons are freed from the semi-conductor materials, thereby generating an electric current. To generate substantial amounts of power with PV, individual cells (which produce about 1 watt of direct current electric power) are combined into a weatherproof-unit called a module. Modules can then be connected together into an array, with the power output limited only by the amount of area available. The modular nature of PV arrays allows them to be built in increments to conform more closely to power requirements as demand for electricity grows.

The principal photovoltaic technologies for current commercial power applications use silicon for the semi-conductor materials. Several efforts are underway to improve silicon-based photovoltaic cells, including optical tracking that orients the cell toward the sun, concentrating devices that increase the amount of solar energy hitting the plate, layering materials to absorb more of the energy, and using amorphous thin film techniques to lower production costs. The major PV technologies are briefly discussed below.

Crystalline Cells

Crystalline silicon cells are the earliest and most-established PV technologies. The most popular material has been single-crystal silicon, which had 90% of the global market in 1980 but only 44% (10.8 MW) by 1985 (IEA 1987). Single-crystal silicon PV cells are relatively efficient (production efficiencies are 12-14%; laboratory efficiencies up to 21%), but have lost market share primarily due to the high cost of manufacturing. This involves several energy-intensive stages to produce the large silicon crystal ingots from which wafers are cut (which destroys about half the crystal ingot), then final preparation and assembly.

In response to some of the problems encountered with single-crystal technology, other crystalline technologies have been developed. Polycrystalline silicon cells use a casting process that is less expensive but only slightly less efficient than single-crystal silicon, e.g., commercially-produced cells have a conversion efficiency of 11-12%, with laboratory efficiencies of 18% (IEA 1987). Polycrystalline silicon cells captured about 20% of the global market in 1985. Another alternative is polycrystalline silicon ribbon, which avoids the need to produce slices (or wafers) by producing sheets or ribbons of polycrystalline silicon. The advantages of this technology are the potential for high-speed production and less material waste, although its efficiency is somewhat lower, e.g., production efficiencies are 10-13% and laboratory efficiencies are 17% (IEA 1987). This technology has been commercialized only recently.

Thin-Film Technologies

As an alternative to crystalline technologies, researchers have focused on thin films. Thin-film solar cells can be produced less expensively using less material and automated production techniques. There are many semi-conductor thin-film materials under investigation, including amorphous silicon, copper indium diselenide, gallium arsenide, and cadmium telluride.

Amorphous Silicon. Amorphous silicon cells have received the most attention of the thin-film technologies, supplying 35% of the global market in 1985 (IEA 1987). The vast majority of this was for use in the consumer market, especially calculators. Because this material does not possess the natural photovoltaic properties of crystalline silicon, efficiency levels have been a problem--laboratory efficiencies are about 13%. Additionally, amorphous silicon suffers from a light-induced power degradation problem which can cause a 22-30% loss of power output over time. Thus, large-scale projects can currently expect to achieve about 5% efficiency over the life of the project. Research into this problem continues, with amorphous silicon thin-film cells considered one of the best potential technologies for power applications as efficiencies improve and production costs are lowered.

Other Semiconductor Materials. Other materials are being investigated that do not utilize silicon, including copper indium diselenide, gallium arsenide, and cadmium telluride. Copper indium diselenide is attractive due to its high efficiency (up to 12% currently) and stability when exposed to sunlight over extended periods. Gallium arsenide technologies have achieved the highest efficiency of any PV material (29%, Poole, 1988), but are also some of the most costly. Research continues on production processes, such as electroplating, that would significantly reduce current production costs.

Multi-Junction Technologies

Multi-junction, or tandem, technologies combine the characteristics of two or more different PV technologies to take advantage of different light absorption characteristics, thereby increasing total cell efficiency (e.g., two-junction devices can achieve efficiencies of 18-35%; U.S. DOE, 1987c). This technique has been used to produce the most efficient solar cell to date--a 31% efficient cell that combined a single-crystal gallium arsenide cell and a single-crystal silicon cell (Poole, 1988). Multi-junction devices are also thought to be a critical component of solar concentrators, which are optical systems designed to improve PV output by increasing the amount of sunlight striking a cell by ten to a thousand times. In combination these technologies may help to achieve in practice the 25-30%

efficiency range considered critical for utility applications (U.S. DOE, 1987c). Multi-junction thin film technologies are also expected to become more important as multi-layering increases system costs proportionately less than the resultant increase in efficiency.

ADDITIONAL PRIMARY RENEWABLE ENERGY OPTIONS

There are opportunities for increased use of additional renewable energy sources, such as hydroelectric, wind, geothermal, and ocean energy. Many of these resources are utilized today (often to supply electricity) and, with continued research and development, have the potential to make important contributions to meeting future energy needs without increasing emissions of greenhouse gases.

Hydroelectric Power

Hydro power currently provides the largest share of renewable electricity generation in the U.S. and globally. In the U.S., hydroelectric capacity accounted for 10-14% of total electricity generation for the years 1983-1987 (U.S. DOE, 1988). Globally, hydroelectric generation accounts for about 20% of total electricity and 7% of primary energy production (United Nations, 1988). The technical potential exists to expand the contribution of hydro at least by a factor of two by the year 2025.

Industrialized Countries

Traditional large-scale hydropower projects are no longer a significant option for most industrialized countries. Many of the most attractive sites have already been exploited in these countries and remaining potential sites are often highly valued in their natural state for recreational, wilderness or ecological purposes. The U.S. has more operational large hydroelectric capacity than any other country in the world. However, new sites are no longer being developed, and the U.S. Bureau of Reclamation, the federal agency historically responsible for large dam-building projects in the West, announced in 1987 that its mandate to develop new water supplies has virtually expired and that it would be contracting in size and shifting its focus to other activities over the next decade (Shabecoff, 1987).

One exception among industrialized countries is the potential for greatly expanding hydroelectric generating capacity in Canada. The U.S. Department of Energy recently identified potential hydro sites in Canada which, if developed, could more that double peak hydro generating capacity in Canada (from about 55 GW to over 127 GW). This level of expansion would not be required to meet projected Canadian demand for many years. However, excess capacity developed in Canada could be used to generate power for transmission to the U.S. where it could compete favorably with other generation options in many regions. The DOE analysis estimates that U.S. imports of power from Canada could more than double by 2010 if the potential hydro sites discussed above were developed (U.S. DOE, 1987d). In lieu of this hydro development, additional generating capacity in the U.S. during this period would predominantly be fossil-fueled. Thus, displacing U.S. capacity additions with Canadian hydro development would reduce CO_2 emissions. However, any hydro development raises potential bilateral and environmental issues with Canada that would need to be resolved.

Expansion of small-scale hydropower (e.g., less than 30 MW) could be an option in many industrialized countries. In the U.S. up to 10 GW of potential capacity additions in this category have been identified (U.S. DOE, 1987a). Other OECD countries, such as Canada and West Germany, are evaluating the potential for expanding small-scale hydroelectric generation (Shea, 1988).

In the USSR and Eastern Europe, there appears to be significant technical potential for expanding both large- and small-scale hydro use. In 1981, hydroelectric generation provided about 13% of total electricity in the USSR. Soviet researchers estimated that this was only about 19% of the country's potential large hydro capacity. Much of the untapped potential is in Siberia, requiring potentially costly long distance transmission to reach major load centers (Hewitt, 1984). In Eastern Europe there are indications that opportunities for large hydro projects still exist as well. Between 1980 and 1985 Romania increased its hydroelectric capacity by 2.5 GW, which was more than a 70% increase in total capacity (World Bank, 1984).

Opportunities also exist for expanding small-scale hydro in the USSR and Eastern Europe. Poland, for example, has recently initiated a program to rehabilitate 640 small dams that had fallen into disrepair and return them to electric generation (Shea, 1988).

Developing Countries

In developing countries the potential for large-scale and small-scale hydro development is very large. For example, by 1980 it is estimated that North America and Europe had developed 59% and 36% of their large hydropower potential, while in contrast, Asia, Africa, and Latin America were estimated to have developed only 5-9% of potential resources. In fact, most large-scale hydro development in the 1980s has taken place in the developing countries.

Between 1980 and 1985, hydro capacity additions in twelve developing countries totaled over 38 GW (over 8% of total generating capacity in developing countries). Several developing countries, notably Brazil, China, and India, have ambitious large hydro development programs planned for the future. Total capacity additions in developing countries could exceed 200 GW by 1995 if these plans are implemented (World Bank, 1984).

There is some question, however, if these plans will be fully implemented. A recent study by the U.S. Agency for International Development (U.S. AID, 1988b) points out that many developing countries are finding it increasingly difficult to finance capital-intensive power projects, especially hydro, which have construction periods of 10 years or more. In addition, the AID and others have pointed out that concerns about ecological and land use impacts such as submergence of forested areas as well as resettlement impacts of large hydroelectric projects may slow such development in the future.

As in industrialized countries, there is also significant potential for small-scale hydro potential in developing countries. At least 28 developing countries already have active programs for developing small-scale hydropower (World Bank, 1984). Equipment for small-scale hydro generation is now manufactured in a number of developing countries, resulting in designs that are both less costly and more suitable to local conditions (U.S. AID, 1988a).

Wind Energy

Wind-powered turbines were first connected to electric power systems in 1941. Curently, there are several technologies available, primarily horizontal axis wind turbines and vertical axis wind turbines. Under optimal conditions, these systems can produce power at 10 to 15 cents per kilowatt-hour, or about two to three times more expensively than conventional fossil powerplants. The goal is to reduce these costs such that in areas with wind resources, these systems can be used economically. In particular, wind energy systems may be very suitable for remote sites where the cost of conventional generation technologies may also be quite high.

Considerable improvement in the performance and economics of wind electric generation was achieved in the early 1980s. In California, electricity generated from "wind farms" increased from 10 terajoule-hours to 16 petajoule-hours (primary energy equivalent) while capital costs fell from $3,100 to $1,250/kw between 1981 and 1987 (Shea, 1988). The Department of Energy reports that the cost of electricity from wind turbines has fallen from about 30 cents/kwh to 10-15 cents/kwh in the 1980s. DOE projects that this improvement will continue and that wind energy could provide as much as 0.7 EJ of electricity in the U.S. by 2005 (DOE, 1987a).

Considerable international attention is now being paid to wind energy. Wind farms are being installed in Denmark, the Netherlands, Great Britain, Greece, and Spain (IEA, 1987). Other nations that have announced plans for expanded wind energy development include China, Australia, Belgium, Israel, Italy, the Soviet Union, and West Germany (Shea, 1988).

Geothermal energy

Geothermal energy is thermal energy stored in rocks and fluids within the earth. It has been estimated that approximately 10% of the world's land mass contains accessible geothermal resources that could theoretically provide hundreds of thousands of megawatts of energy for many decades (IEA, 1987b). As indicated in Table 7-10, geothermal resources suitable for generating electricity are extensive and geographically widespread. From a global warming context, several countries with the most extensive geothermal potential, e.g., the U.S., China, and the USSR, are also currently heavily dependent on coal consumption. Geothermal energy may, in these countries, provide one option for displacing coal as a source of baseload electricity generation and industrial heat. Significant geothermal resources also exist, and are being developed, in several Pacific Rim countries, where economic growth rates, and thus demand for additional energy, is expected to be high.

While certain types of geothermal resources, specifically hydrothermal and geopressured reservoirs, are not strictly renewable on a human time scale, resources are so extensive that with

TABLE 7-10

Estimates of Worldwide Geothermal Electric Power Capacity Potential (in Megawatts)

Country	MW	Country	MW
Argentina	19,950	Kenya	79,450
Bolivia	63,100	Korea (N. & S.)	79,450
Cameroon	15,150	Mexico	257,050
Canada	446,700	Morocco	19,950
Chile	30,200	New Guinea	30,900
China	537,050	New Zealand	30,900
Columbia	77,650	Nicaragua	33,900
Costa Rica	12,600	Peru	302,000
Ecuador	100,000	Philippines	67,600
El Salvador	5,000	Portugal	1,000
Ethiopia	154,900	Saudi Arabia	15,850
Greece	8,900	Soviet Union	239,900
Guadeloupe	387	Spain	5,900
Honduras	12,600	Taiwan	8,150
Iceland	22,900	Tanzania	6,200
India	15,200	Turkey	87,100
Indonesia	436,500	U.S.	501,200
Iran	75,850	Venezuela	39,800
Italy	33,900	Vietnam	37,150
Japan	79,450		

Source: U.S. DOE, 1985c.

careful phasing and reservoir management, geothermal energy can make a significant long-term contribution to global energy needs. Unlike renewable energy sources such as solar radiation and wind, geothermal resources are available on a constant basis, making them suitable for baseload electricity generation and industrial applications without the storage problems associated with intermittent energy sources.

There are several types of geothermal resources that require somewhat different approaches for exploitation. Hydrothermal resources contain hot water and/or steam trapped in fractured or porous rock at accessible depths (e.g., 100-4500 meters). These are the most commonly used resources currently, and the only resources currently commercially exploited. Technology for exploiting these resources involves sinking wells, extracting the hot fluids, and using the steam or hot water for electricity generation or direct heat applications. Steam can be used directly in steam electric generating turbines. Hot water resources are either "flashed" to produce steam, or used to vaporize another working fluid which in turn drives a turbine.

Another type of geothermal resource of long-term interest is hot dry rock. These potential resources are widely distributed around the world, but more difficult to exploit than hydrothermal resources. To extract heat from hot dry rock, it is necessary to inject liquid into one well and withdraw it through another well after it has absorbed heat. Considerable research is underway to improve technologies for extraction of energy from hot dry rock. A geothermal resource still at the conceptual stage of development is magma which is liquefied or partially-liquefied rock. Potential resources may be greater than any other geothermal resource and the very high temperatures available suggest that power could be economically produced; however, development of the necessary technologies is seen as a major challenge.

Geothermal energy is currently used in several countries for direct heat and electricity generation. Table 7-11 shows the extent of direct heat use in 1984. Table 7-12 indicates the installed capacity for geothermal electricity generation by country in 1985. Although they represent only a small fraction of total energy use, these facilities have demonstrated the commercial viability of geothermal technologies. In the U.S. geothermal systems currently produce electricity at a cost that is competitive with coal and nuclear plants, and the average geothermal unit today is available on-line more than 95% of the time (U.S. DOE, 1987a). The Department of Energy projects that U.S. geothermal electric capacity will more than double by 1995 to about 4.7 GW.

Geothermal energy may also play an even more important role in some developing countries. Eight developing countries currently have installed geothermal electric capacity, and about 50 more have been identified as having potential for geothermal development (U.S. AID, 1988a). In the 1980s, the costs of geothermal technology have come down considerably, and small-scale, ready-to-install generators (1-15 MW) have also been developed and proven reliable. These and other developments should make geothermal electricity more attractive to many developing countries (U.S. AID, 1988a).

Ocean Energy

There are several types of potential ocean energy sources, including thermal gradients and waves. Research is underway in many countries, including the U.S., to develop technologies that can exploit these resources. In one technology, cold water located deep in the ocean is used to condense a working gas such as freon or ammonia. The liquid then is reconverted to gas by warm surface waters and used to drive a turbine and generate electricity. Current costs for such a system are roughly three times higher than commercial alternatives, and significant technological uncertainties remain regarding system components and operation in an ocean environment.

TABLE 7-11

Capacity of Direct Use Geothermal Plants In Operation - 1984

(For countries having capacity above 100 MW)

Country	Power MW	Energy GWh	Load %
China	393	1945	56
France	300	788	30
Hungary	1001	2615	30
Iceland	889	5517	71
Italy	288	1365	54
Japan	2686	6805	29
New Zealand	215	1484	79
Romania	251	987	45
Soviet Union	402	1056	30
Turkey	166	423	29
United States	339	390	13
Other	142	582	47
Total	7072	23957	39[1]

[1] Based on total thermal power and energy.

Source: IEA, 1987.

TABLE 7-12

Geothermal Powerplants On-Line As Of 1985

Country	No. Units	Type(s)[a]	MW
United States	56	DS,1F,2F,B	2022.11
Philippines	21	1F	894.0
Mexico	16	1F,2F	645.0[b]
Italy	43	DS,1F	519.2[b]
Japan	9	DS,1F,2F	215.1
New Zealand	10	2F	167.2
El Salvador	3	1F,2F	95.0
Kenya	3	1F	45.0
Iceland	5	1F,2F	39.0
Nicaragua	1	1F	35.0
Indonesia	3	DS,1F	32.25
Turkey	2	1F	20.6
China	12	1F,1F,B	14.32[b]
Soviet Union	1	F	11.0
France (Guadeloupe)	1	2F	4.2
Portugal (Azores)	1	1F	3.0
Greece (Milos)	1	1F	2.0[b]
Totals	188		4763.98

[a] DS = dry steam; 1F,2F = 1- and 2-flash steam, B = binary.
[b] Includes plants under construction and scheduled for completion in 1985.

Source: IEA, 1987.

Another technology would exploit wave energy using a device in which wave motion would compress trapped air. The compressed air would then be used to drive a turbine and generate electricity. This system is also currently unproven and expensive. Further, the output of a wave-based system would fluctuate with wave conditions, which would not necessarily match well with electricity load requirements. As with many other renewable technologies, economic and reliable energy storage would be necessary to make this option viable.

NUCLEAR POWER

This section discusses the potential role for nuclear power to meet future energy needs. From the perspective of global warming, nuclear power technologies are attractive in that they do not emit greenhouse gases. As will be discussed, however, there are other problems that beset the nuclear power industry. The first part of this section discusses fission technologies; nuclear fission is the technology currently used in operating nuclear powerplants. One of the key attributes of this technology is its need for fissionable, radioactive material in order to operate. The last part of this section discusses fusion technology, which is a longer term nuclear option currently in the research and development stage. Unlike fission technologies, fusion technologies would not require large inventories of radioactive materials such as uranium and plutonium for their operation.

Nuclear Fission

Nuclear fission technology is an important source of electricity in many regions of the world. For example, in the U.S. nuclear plants provided about 17% of total electricity generated in 1987. This total is projected to increase throughout the remainder of this century as about 20 GW of new nuclear powerplants, which are currently under construction, are completed. However, the prospects for further capacity additions are clouded. In the words of the U.S. Department of Energy, "No

best copy available

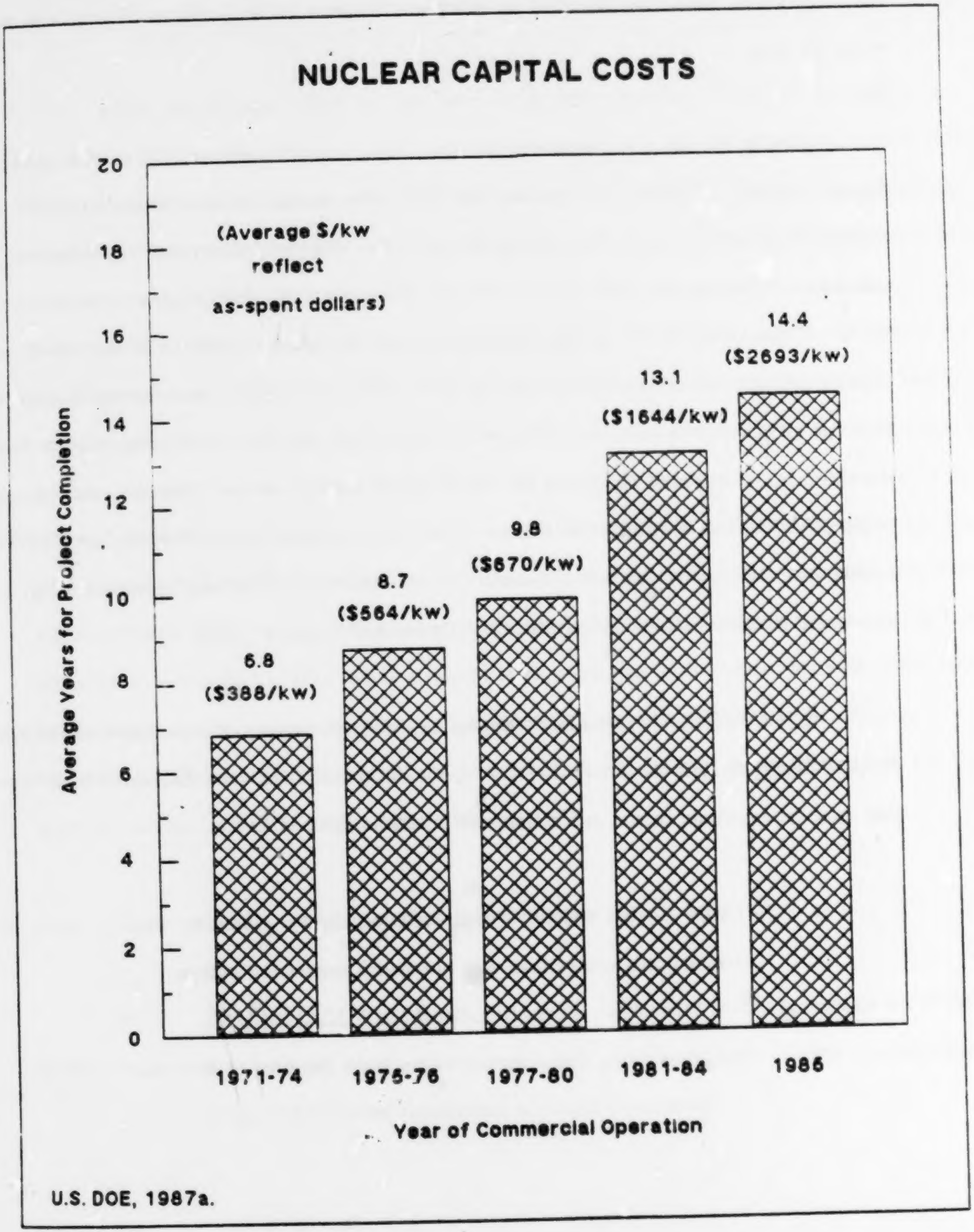
additional orders for nuclear powerplants are likely in this country until the conditions of the past few years are changed" (U.S. DOE, 1987a). Moreover, between 2000 and 2015, about 40% of existing nuclear powerplant capacity will have to retire unless current operating licenses are extended beyond their expiration dates.

The situation is somewhat similar in many other industrialized countries. The International Energy Agency reports that nuclear energy was the fastest growing fuel for electricity generation in the OECD countries between 1985 and 1987. However, the report continues: "It should be kept in mind, however, that present additions to nuclear capacity come from stations authorized in the second relatively intense "cycle" of nuclear plant construction activity in the 1970s. Compared with some 239 GW of nuclear capacity operating in the OECD countries at the end of 1987, around 52 GW are under construction" (IEA, 1988). In addition, planned nuclear electricity production in the 1980s in the USSR has been consistently behind schedule due to construction delays. By 1986, nuclear generation was providing about 10% of electricity in the USSR. In the wake of the Chernobyl disaster of April 1986, the nuclear program in the USSR is experiencing further delays and future contributions are difficult to project (IEA, 1988).

Nuclear power has been beset by a series of problems. Plant capital costs have increased so dramatically that new nuclear powerplants are no longer considered economical (see Figure 7-15). Powerplant lead times (i.e., the time for project initiation to completion) are greater than ten years, increasing project risk. Additionally, in many countries such as the U.S., the regulatory environment is generally unfavorable toward large, long-term capital investments and nuclear powerplants in particular (U.S. DOE, 1987a).

Public opposition to nuclear powerplants is strong, in part due to concerns about safety in the aftermath of the accidents at Three Mile Island and Chernobyl. In addition to plant safety, waste

FIGURE 7-15



U.S. DOE, 1987a.

disposal is an issue of major concern. Although several countries utilizing nuclear power are working on the problem, none have identified an acceptable solution to the problems of long-term nuclear waste disposal.

Finally, the nuclear weapons proliferation issue must be addressed if nuclear power is to become publicly acceptable. A present day 1000 MW nuclear plant produces some 141 kg of fissionable plutonium annually in its spent fuel. For comparison, it takes less than 10 kg of fissionable plutonium to make a nuclear weapon. Currently, this spent, intensely radioactive fuel is stored at plant sites. If nuclear power were to be greatly expanded in the future, limited supplies of uranium worldwide would rapidly force a shift from today's "once through" nuclear cycles (i.e., the nuclear fuel is only used once) to fuel cycles involving the reprocessing of spent fuel and the recycling of recovered plutonium for use as fuel in present reactor types and a new generation of plutonium breeder reactors. The amount of fissionable material required would pose a formidable institutional challenge to the world community to safeguard relatively large quantities of plutonium that would circulate in worldwide commerce (Ogden and Williams, 1988).

In the U.S., the Department of Energy has recognized many of these potential obstacles. In its 1987 Energy Security report (U.S. DOE, 1987a), the U.S. DOE identified three basic obstacles that must be overcome before new orders will be forthcoming:

- Given current reactor designs and regulatory processes, nuclear power is not economically competitive with alternative generation options.

- Public concerns about reactor safety make licensing of new plants difficult.

- Currently unresolved questions about the viability of long-term waste disposal options have become a significant barrier to expansion of nuclear power.

DOE has initiated efforts to deal with all of these problems. First, it has underway a research program aimed at the development of improved reactor designs. Program goals include new designs for "enhanced safety, increased simplicity, and improved reliability." To meet these goals, the new designs incorporate innovative concepts of passive safety that hopefully would ensure that any equipment or operator failure would cause the plant to shut down automatically. A second important attribute of the advanced designs is standardization of designs, which could reduce cost, shorten the permitting process, and improve reliability and safety. Third, the new designs are for smaller, modular units, which should make them more compatible with the utility industry's needs for smaller capacity addition. Another design concept is that the portion of the plant that is actually within the nuclear containment vessel can be minimized and modularized, thereby allowing the balance of the plant to be built to standard construction specifications. An example of this approach is Sweden's ASEA-ATOM's PIUS reactor, which places the steam generator and primary pumps outside the containment vessel (EIA, 1988). More stringent safety standards for nuclear powerplants could then focus on the smaller nuclear component. Ultimately, the nuclear portion may be designed to be fabricated at the manufacturing plant and transported in its entirety to the powerplant site for insertion into the remainder of the plant (Griffith, 1988).

These principles are being applied to several basic reactor types:

- Advanced Light Water Reactor (ALWR). Light water reactor technology is currently the type most widely in use in the U.S. The hope is to develop a standardized design incorporating the lessons of recent experience.

- Modular High Temperature Gas Reactor (HTGR). This is an advanced concept that has not been demonstrated yet but is being designed to provide a next generation nuclear capability that goes further toward meeting the design criteria mentioned above than the ALWR.

- Advanced Liquid Metal Reactor (LMR). For the longer term, designs are being developed that would incorporate the design goals stated above into a potential breeder reactor option.

Finally, on the waste disposal issue, DOE has announced that it will continue to implement the long-term Geologic Repository Program for disposal of high-level wastes while also constructing a Monitored Retrievable Storage (MRS) Facility (U.S. DOE, 1987a). Thus, DOE is attempting to deal with many of the constraints affecting the nuclear power industry. It is difficult to predict at this point how effective these programs will be. In addition, the DOE report does not mention the weapons proliferation problem that is also perceived as a long-term constraint by many observers.

Nuclear Fusion

Nuclear fusion, like nuclear fission, is an attractive power generation technology from a global warming perspective because it does not generate greenhouse gas emissions. Fusion power has two key advantages over fission power: (1) It uses secure and inexhaustible fuels: lithium and deuterium are obtainable from seawater, and (2) it does not create large inventories of radioactive wastes.

However, fusion reactor technology is only in the early stages of research and development; it is not expected to be a viable technology until after 2025. The costs of development for this technology are expected to be high. To hasten fusion development and to defray the costs that need to be borne by any single country, international cooperative R&D agreements are likely to be signed in the next few years.

ELECTRICAL SYSTEM OPERATION IMPROVEMENTS

One possible option for reducing the amount of greenhouse gas emissions from electricity is to improve the efficiency of transmission, distribution, and storage of electrical power. Each of these areas is discussed below.

Transmission and Distribution

Electrical energy losses from transmission and distribution are normally in the 5-10% range in industrialized countries. When generation is primarily from fossil fuels, as in the U.S., programs to reduce efficiency losses associated with electricity transmission and distribution may provide one option for modest reductions in greenhouse gas emissions. In developing countries, however, it is very likely that significant improvements are technically possible. Many developing countries experience losses of over 20%, even 30%. Relatively inexpensive and straightforward technological solutions exist for upgrading utility transmission and distribution systems to recover a major portion of these losses. On the other hand, in many countries it is estimated that half of the "controllable" losses are due to theft (U.S. AID, 1988b); despite many reasons for reducing these thefts, it is not clear whether a straightforward solution to these electricity thefts exists nor would this mean a significant reduction in greenhouse gas emissions, except to the extent demand is reduced as consumers are charged for the power they use.

Electric utility companies normally operate their systems and interconnections with other systems in such a way as to minimize generation costs, subject to a number of other constraints.

Thus, powerplants with the lowest variable operating (including fuel) costs would be operated more of the time, and power available from other utility systems would be purchased when its cost is lower than the incremental cost of generating additional power within the system.

Within this framework, there may be some flexibility to shift more of the overall load to non-fossil or natural gas-fired capacity without greatly increasing overall generating costs. Although difficult to achieve institutionally, such alternative dispatching options may be technically feasible and cost-effective in the near term. This could include "wheeling" power from region to region to take maximum advantage of non-fossil generating capacity. On its largest scale, this type of strategy could result in international electricity transfers from countries with less carbon-intensive generating capacity to countries with more carbon-intensive available options. For example, expanded Canadian power imports to the U.S. based on hydroelectric generation would be one such possibility.

Superconductors

Superconductors offer no resistance to electrical flow. Recently, breakthroughs in superconductivity research has increased the prospects that this technology could be applied to power production. Until recently, superconductivity could only be achieved in extremely cold environments (e.g., more than 200°C below zero). The superconductivity effect can now be achieved at much higher temperatures, although they are still well below ambient conditions. In the long term, superconductivity could significantly improve the transmission of power. Conventional transmission systems lose about 8% of the power they conduct; superconductors could greatly reduce, if not eliminate, these losses. Superconductivity could also be beneficial for power production. For example, several technologies use electromagnets, including the MHD system discussed above. During the power production process electromagnets are typically the source of some lost power.

Superconductors could reduce the energy lost in generating power by reducing these losses associated with electromagnets. Also, as discussed below, superconductivity could be useful for energy storage.

Storage Technologies

There are a variety of technologies currently available or under development for energy storage. Storage systems can perform several tasks, including:

- Load-leveling, which would allow inexpensive baseload electricity to be stored during periods of low demand and released during periods in which the marginal cost of electricity is high, e.g., powerplants could be run during the night and the power stored to meet peak requirements in the afternoon. One caveat is that storage may allow baseload coal to substitute for natural gas, increasing greenhouse gas emissions, unless renewable energy sources are used.

- Spinning-reserve, in which the energy would be used to backup failed generating systems.

- System-regulation, i.e., to balance a utility's constantly-shifting generation and load requirements.

The development of adequate energy storage systems could be particularly crucial for the competitiveness of many renewable energy technologies which can only produce power when the resource is available, e.g., during daylight hours for solar or when the wind is blowing for wind energy systems. To enhance their competitiveness, renewable technologies could be used in tandem with storage systems that would allow power to be generated whenever available and then stored until needed.

Types of Storage Technologies

There are many different types of energy storage systems, including pumped storage, batteries, thermal, compressed air, and superconducting magnetic energy storage. Several major energy storage systems are discussed below.

Pumped Storage. Pumped storage is a hydroelectric power storage option that has been used recently by the electric utility industry to meet electricity requirements during periods of peak demand. With this system water is pumped from a lower storage reservoir to an upper storage reservoir during off-peak hours, using electricity from a baseload powerplant (which is frequently coal-fired or nuclear). During peak demand hours, the water is released to the lower reservoir much like it would be at a typical hydroelectric dam. This system essentially stores power from the baseload powerplant when it is not needed for use during peak demand periods when the baseload plant is already committed 100% to meeting the peak power requirements.

While there are numerous pumped storage plants in the U.S., their efficiency is low and additional siting is likely to be difficult if they involve large, above-ground reservoirs. When underground reservoirs are used, the systems are only economical in very large facilities (e.g., 1000 MW).

Batteries. Batteries are attractive primarily for their flexibility; because they are modular, plants can be constructed quickly on an as-needed basis. Recent research and development has focused on advanced lead-acid batteries and zinc-chloride batteries. Lead-acid battery technology has been used for decades, e.g., in automobiles, although their use in utility applications may be limited by their capital costs. Due primarily to the lower cost of the construction materials, the zinc-chloride battery is expected to be less expensive than the lead-acid battery in the longer term; possibly less than $500/kW compared to $600/kW or higher for lead-acid batteries (OTA 1985). Plans to test both types of batteries on a commercial scale are currently being planned. Other battery technologies that could be available in the longer term include zinc-bromide, sodium-sulfur, iron-chromium, and lithium-iron sulfide batteries.

Compressed Air Storage. Compressed air energy storage (CAES) uses off-peak electricity to store energy in the form of compressed air in an underground cavern such as salt reservoirs, hard rock reservoirs, or aquifers. The compressed air is used in tandem with natural gas or oil in a modified gas turbine where the compressed air is used in lieu of a conventional compressor in the turbine cycle, thereby allowing the turbine efficiency to increase up to three times its normal efficiency (OTA 1985). CAES is dependent on geological characteristics that can be found in about 3/4 of the U.S. and uses technology that is well-advanced. However, no CAES facility has yet been built in the U.S.; there is a facility that has been operating since 1978 in West Germany. There are two sizes proposed for CAES plants; a mini-CAES (about 50 MW) costing about $392/kW and a maxi-CAES (about 220 MW) costing about $515/kW; construction lead times are estimated to be 4 to 8 years (U.S. OTA, 1985).

Superconducting Magnetic Energy Storage. Superconducting magnetic energy storage (SMES) would function like more conventional storage technologies, but would be able to store energy with an efficiency of approximately 95% compared to 75% for pumped storage or 65% for battery storage (Schlabach 1988). At this time SMES is clearly a long-term technology pending further improvements in basic superconductivity design.

HYDROGEN

One concept for reducing CO_2 emissions is the long-term phaseout of a carbon-based economy and the adoption of one utilizing hydrogen and electricity as complementary energy currencies. Hydrogen would serve as an "energy carrier" since electricity or some other source of power is required to produce it. Hydrogen is attractive for this role because it is nonpolluting, portable, and relatively safe. Hydrogen could be produced in a number of ways, including chemical processes beginning with coal or natural gas, and electrolysis using electricity from the full range of potential electricity production options. Of course, production chemically from fossil fuels or the use of fossil-based electricity would not provide significant long-term reductions in greenhouse gas emissions. However, these technologies are currently available and could play a role in a transition to greater use of hydrogen as an energy source (Harvey, 1988).

One technology under development holds some promise for allowing hydrogen to be generated from fossil fuels without CO_2 emissions. The process, known as hydrocarb, produces hydrogen and carbon black through a process of gasification and distillation. When coal is used as the feedstock, approximately 20% of the energy value is converted into hydrogen. The carbon black produced could be disposed in mines or other disposal facilities. Biomass can be used as the feedstock, although it is a less efficient source of hydrogen (Grohse and Steinberg, 1987).

While large-scale hydrogen use would have to be considered a long-term option, this fuel could begin to make contributions in the near term. Researchers at Princeton University have suggested that use of hydrogen as a transportation fuel in urban areas may be its first significant role in replacing traditional fuels. This is because existing transport fuels are high-priced premium fuels such that the economics would be more favorable, and because urban air quality problems are already forcing many cities to look for alternatives to gasoline and diesel fuel in the transportation sector.

They further suggest that recent and projected improvements in the economics of amorphous silicon photovoltaic cells may make production of hydrogen fuel for transportation use from solar PV electricity cost competitive in some areas of the U.S. before the end of this century (Ogden and Williams, 1988).

Another attractive feature of hydrogen that would be helpful in a long-term transition away from fossil fuels is that it can substitute relatively easily for natural gas in many applications. For example, natural gas space heating could be replaced by hydrogen over the long term, natural gas pipelines could be used to transport hydrogen, and hydrogen is the basic fuel for fuel cells. Storage of hydrogen could utilize salt mines, aquifers, and depleted oil and gas fields for large needs and liquid hydrogen and metal hydrides for small applications.

In a long-term hydrogen economy, non-fossil energy could be provided by a variety of renewable sources, with conversion to hydrogen accomplished by the electrolysis of water. Conversion efficiencies in producing hydrogen from renewable energy exceed 80% and efficiencies for conversion back to energy in fuel cells range from 58-70%.

PART THREE: INDUSTRY

Figure 7-16 illustrates the overall current contribution of industrial processes (excluding energy) to the greenhouse warming problem. By far the largest component is the production and ultimate release to the atmosphere of chlorofluorocarbons (CFCs), halons, and chlorocarbons. Other industrial processes are relatively minor (but growing) contributors: CO_2 is emitted from cement manufacture and methane (CH_4) is produced by solid waste landfills. In addition, industrial process emissions of carbon monoxide contribute to atmospheric chemistry, which indirectly affects the concentration of tropospheric ozone and methane.

CFCs AND RELATED COMPOUNDS

As a result of the Montreal Protocol (discussed in Chapter IX), emissions of the most important CFCs will be capped in the near future and will be reduced to half of 1986 levels by 1998. Halons will be frozen at 1986 levels beginning in 1992. Other related compounds, not covered by the protocol, are projected to grow in the No Response scenarios, partly because some of these compounds will be used as substitutes for the regulated compounds.

Some of the substitute compounds affect greenhouse warming but generally to a much smaller degree than do the controlled substances. In addition, most of the unregulated compounds have much shorter atmospheric lifetimes, which further decreases their impact on the greenhouse problem.

In the No Response scenarios, we have assumed general compliance with the Montreal Protocol (100% in U.S., 94 % in other industrialized countries, and 65% in developing countries). Figure 7-17 shows projections for future emissions for the regulated compounds, as well as the

FIGURE 7-16

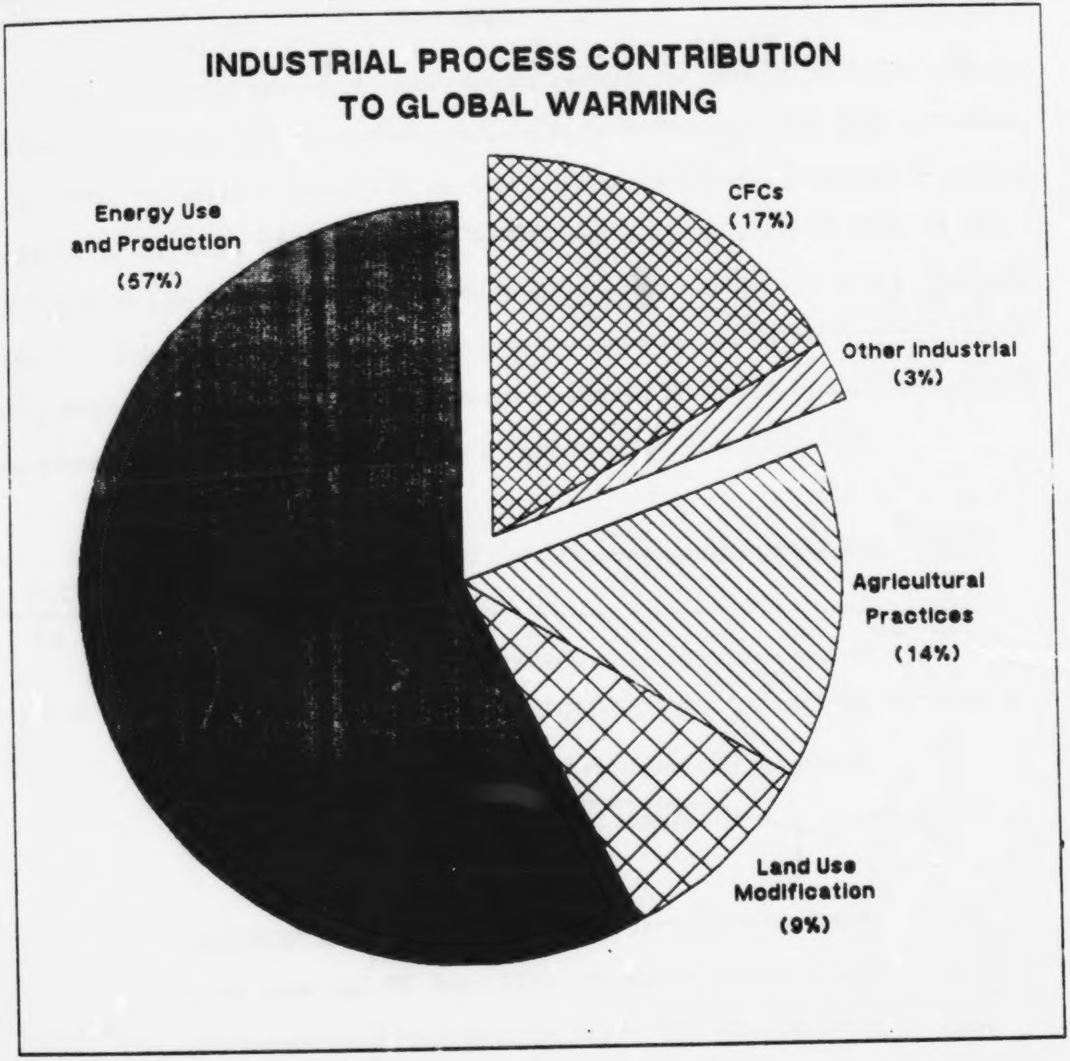
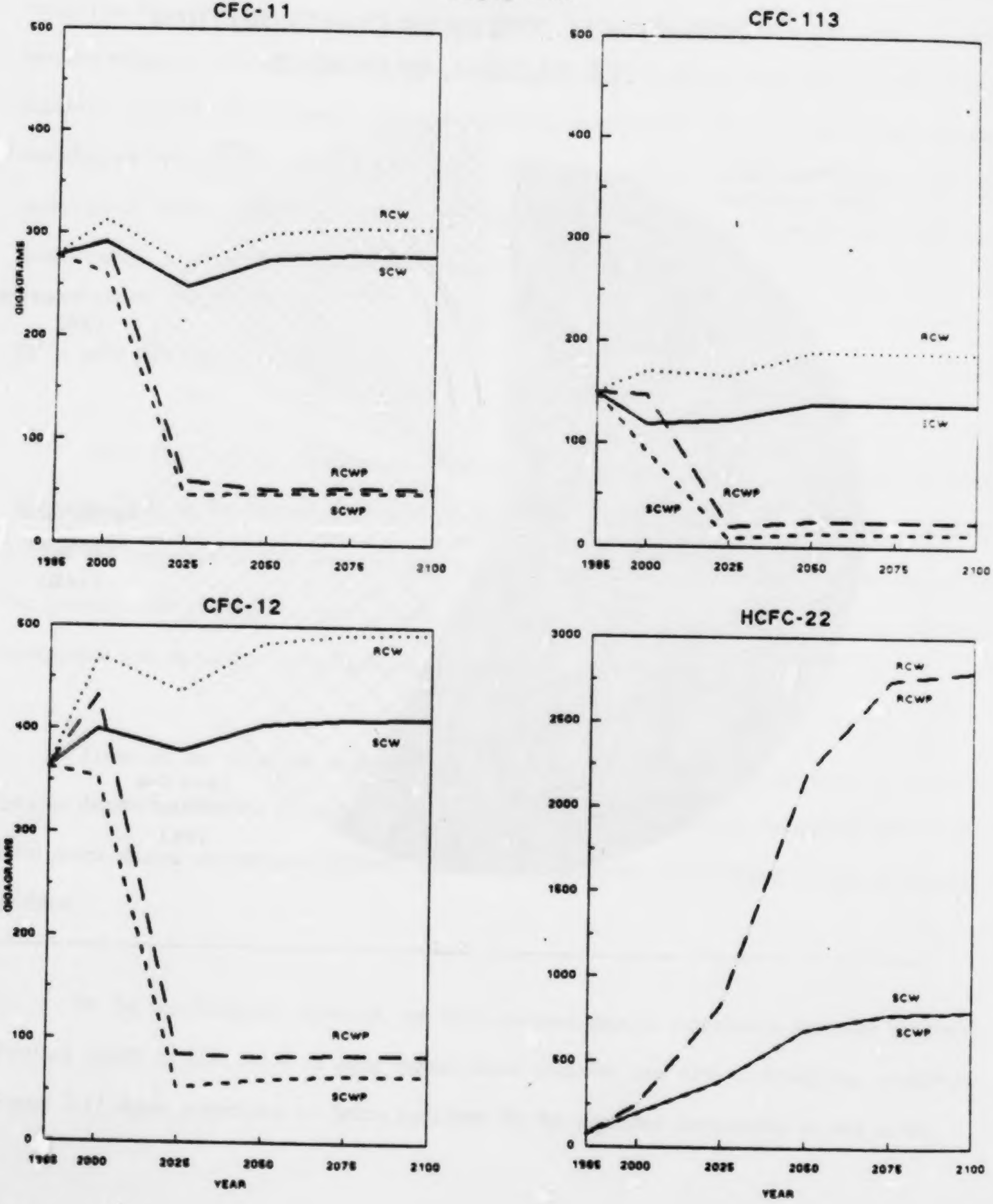

INDUSTRIAL PROCESS CONTRIBUTION
TO GLOBAL WARMING
Energy Use
and Production
(57%)
CFCs
(17%)
Other Industrial
(3%)
Agricultural
Practices
(14%)
Land Use
Modification
(9%)

FIGURE 7-17

EMISSIONS OF MAJOR CFCs

(Gigagrams)



growing global emissions of unregulated substitute compounds, which have some radiative forcing impact.

A considerable amount of recent analysis evaluates the potential of further reducing emissions of CFCs and related compounds (see, for example, Hoffman and Gibbs, 1988, or Makhijani et al., 1988). As shown in Figure 7-17, the SCWP and RCWP scenarios incorporate a complete phase-out of the major CFCs and Halons by 2003 and a cap on global emissions of methyl chloroform at 1986 levels (100% participation in industrialized countries and 85% in developing countries). This phase-out schedule is feasible given that substitutes and alternative technologies now being developed and tested are expected to become available over the next decade -- as a result of the considerable research currently underway in response to the Montreal Protocol.

Use and emissions of CFCs could be reduced by three possible mechanisms:

- Chemical substitution - switching from production processes in which CFCs are used to those in which other chemicals are used; for example, using FC-134a or blends of other non-fully halogenated HCFCs instead of CFC-12 in mobile air conditioning.

- Engineering controls - in the near term, switching to production technologies that use fewer CFCs per unit of output, such as recycling equipment that collects and recycles CFC emissions during the production of electronics.

- Product Substitution - switching from CFC-using products to other products; for example, replacing CFC-based foam egg cartons with paper-based egg cartons.

This chapter surveys existing and future product substitutes, engineering controls, and chemical substitutes that can reduce use and emissions of CFCs and halons. The information presented is based on a detailed series of industry studies performed by EPA for use in its *Regulatory Impact Analysis* (U.S. EPA, 1987) for stratospheric ozone protection. Unless otherwise noted, information in this section is drawn from U.S. EPA (1988b).

Technical Options For Reducing Emissions

Chemical Substitutes

Several chemical substitutes that have physical properties (e.g., boiling point) similar to those of CFCs either do not contain chlorine or have short atmospheric lifetimes that reduce their potential to deplete stratospheric ozone.

FC-134a and blends of non-fully-halogenated HCFCs appear to be the most promising chemical substitutes for refrigeration and air conditioning applications, including commercial chillers and mobile air conditioning, and along with HCFC-141b and HCFC-142b appear to be likely alternatives to CFC-11 and CFC-12 in production of polystyrene sheet and polystyrene boardstock. Several major chemical producers have begun limited production of FC-134a. An international consortium of chemical producers has been formed to undertake toxicity testing of FC-134a and other chemical substitutes.

HCFC-141b and **HCFC-123** are expected to become commercially available in the early 1990s and could replace CFC-11 currently being used in manufacturing slabstock flexible polyurethane foam and rigid polyurethane foam. In blends with HCFC-22, **HCFC-142b** appears to be an option for replacing the remaining "essential" CFC use in aerosols.

HCFC-22 is currently used in residential air conditioners and might be used in commercial chillers. It could substitute for CFC-11 and CFC-12 as a leak-testing agent in several refrigeration applications. Mixtures of HCFC-22 and other compounds could be used in mobile air conditioners.

HCFC-22 has already been accepted as a substitute for CFC-blown polystyrene sheet products. It was recently approved by the Food and Drug Administration as an alternative blowing agent for use in food packaging. The Foodservice and Packaging Institute, in concert with several environmental groups, recently announced an industry-wide program to eliminate within one year the use of CFC-11 and CFC-12 use in food service packaging by substituting HCFC-22.

A major manufacturer of extruded polystyrene boardstock recently announced that it will substitute HCFC-22 and other partially-halogenated CFCs in its manufacturing processes beginning in 1989.

Blends of HCFC-22 with **dimethyl ether** and HCFC-142b can be used to replace the remaining "essential" CFC use in aerosols. **Hydrocarbons** have largely replaced CFCs as aerosol propellants in the United States. Other nations can reduce their use of CFCs in aerosol propellants by reformulating aerosol products.

Ethylene oxide (EO) is currently blended with CFC-12 for use in sterilization of medical equipment and instruments. Reductions in CFC-12 use could be achieved by using pure EO, a blend of CO_2/EO, radiation, or the use of CFC substitutes.

Terpene-based solvents can be used instead of CFC-113 to clean electronic components. One major manufacturer expects to replace one-third of all its CFC use in electronics manufacturing with terpene-based solvents. **Aqueous cleaning** can also reduce CFC-113 use in many applications for cleaning electronic components.

Engineering Controls

Recovery and recycling can reduce CFC emissions from several applications. Recovery and recycling during servicing of air conditioning and refrigeration equipment, such as commercial chillers and mobile air conditioning units, can achieve large reductions in CFC emissions.

Carbon adsorption units could be installed to capture CFC emissions during manufacture of slabstock flexible polyurethane foam. Simple housekeeping improvements and process modifications such as automatic hoists and covers, carbon adsorption, and reclamation and recycling can reduce CFC-113 emissions during solvent cleaning.

Alternative leak-testing agents can reduce halon emissions during discharge testing of total flooding fire-extinguishing systems.

Improved system design can reduce CFC emissions. Attractive techniques in mobile air conditioning include design improvements, such as the use of more refrigerant-tight hose materials, shorter hoses, and improved compressor seals and fittings.

Alternative processes can be used to produce final products without using CFCs. For example, the CFC-blown foam process can be modified to eliminate use of CFC-11, but the foam will be slightly denser as a result. Nearly all uses of molded flexible foam could be converted to water-blown formulations.

Training could reduce unnecessary discharges of CFCs during air conditioning servicing. Adoption of new training procedures, such as use of simulators, could reduce halon emissions during military training exercises.

Product Substitutes

Research efforts are exploring ways to replace the use of CFC-blown insulation in refrigerator walls by insulating vacuum panels. A prototype vacuum panel refrigerator, which could achieve sizeable gains in insulating properties, is currently being built.

CFC-blown slabstock flexible polyurethane foams can be replaced by other products. Fiberfill materials, cotton batting, latex foams, and built-up cushioning that contains springs may be suitable substitutes, but they are more expensive and lack the durability of flexible polyurethane.

Some product substitutes are available for rigid polyurethane foam products. Many alternative products are currently available for use as sheathing or roof insulating materials. Expanded polystyrene foam beadboard, fiberglass, fiberboard, and gypsum, for example, could be used instead of polyurethane foam, as they were 30 years ago when polyurethane foams were not yet manufactured. In some cases, wall and roofing insulation can be made thicker to achieve the same insulating capacity as at present, but the use of foam blown with chemical substances is likely to continue where it offers the advantages of reduced labor costs and smaller bulk and meets a building's energy efficiency requirements.

Some product substitutes are available for poured or sprayed foam, depending on the specific use. In applications such as packaging and flotation, product substitutes are numerous. Combinations of plastic and non-plastic materials can provide equivalent degrees of cushioning, shock resistance, and water resistance. At present, however, no other insulation materials have equivalent ability to be poured or sprayed, nor can other materials of the same thickness insulate as well as rigid polyurethane foams.

Polystyrene sheet competes with many other disposable packaging and single service products, including paper, cardboard, solid plastic, metal foils, and laminar composites of foil, plastic film and paper. Any of these substitutes could eliminate CFC use in food packaging applications.

Current and possible future alternatives to foam boardstock as insulation include a host of product substitutes, including fiberglass board, perlite, expanded polystyrene, fiberboard, cellular glass, insulating concrete, rock wool, vermiculite, gypsum, plywood, foil-faced laminated board, and insulating brick. Greater thicknesses of these alternatives may be required to provide equal energy efficiency.

Pre-sterilized, disposable products are one possible alternative that will enable hospitals to reduce their dependence on CFC-12 for sterilization.

Pump sprays and roll-ons are product substitutes that can replace CFC-propelled personal care aerosols.

Summary of Technical Potential

A recent detailed report examined the available and emerging options for reducing CFCs, as well as halons and chlorocarbons, which are of potential concern for both stratospheric ozone depletion and greenhouse warming (Makhijani et al., 1988). These authors assumed that both CFCs and halons as well as carbon tetrachloride and methyl chloroform would be phased out by the year 2000. The report asserted that technical options are currently available for eliminating all but two of the important applications; however, it is not certain that all of the substitutes proposed are actually available or will perform as hoped.

Given the rapid pace of current technical innovation, however, it is not unreasonable to expect that all sources of industrial emissions could be eliminated over the next decade. However, even the less stringent CFC, halon and methyl chloroform controls assumed in the Stabilizing Policy scenarios were very effective in reducing climate warming commitment. The recent detailed analysis indicates that even more significant reductions are technically possible.

METHANE EMISSIONS FROM LANDFILLS

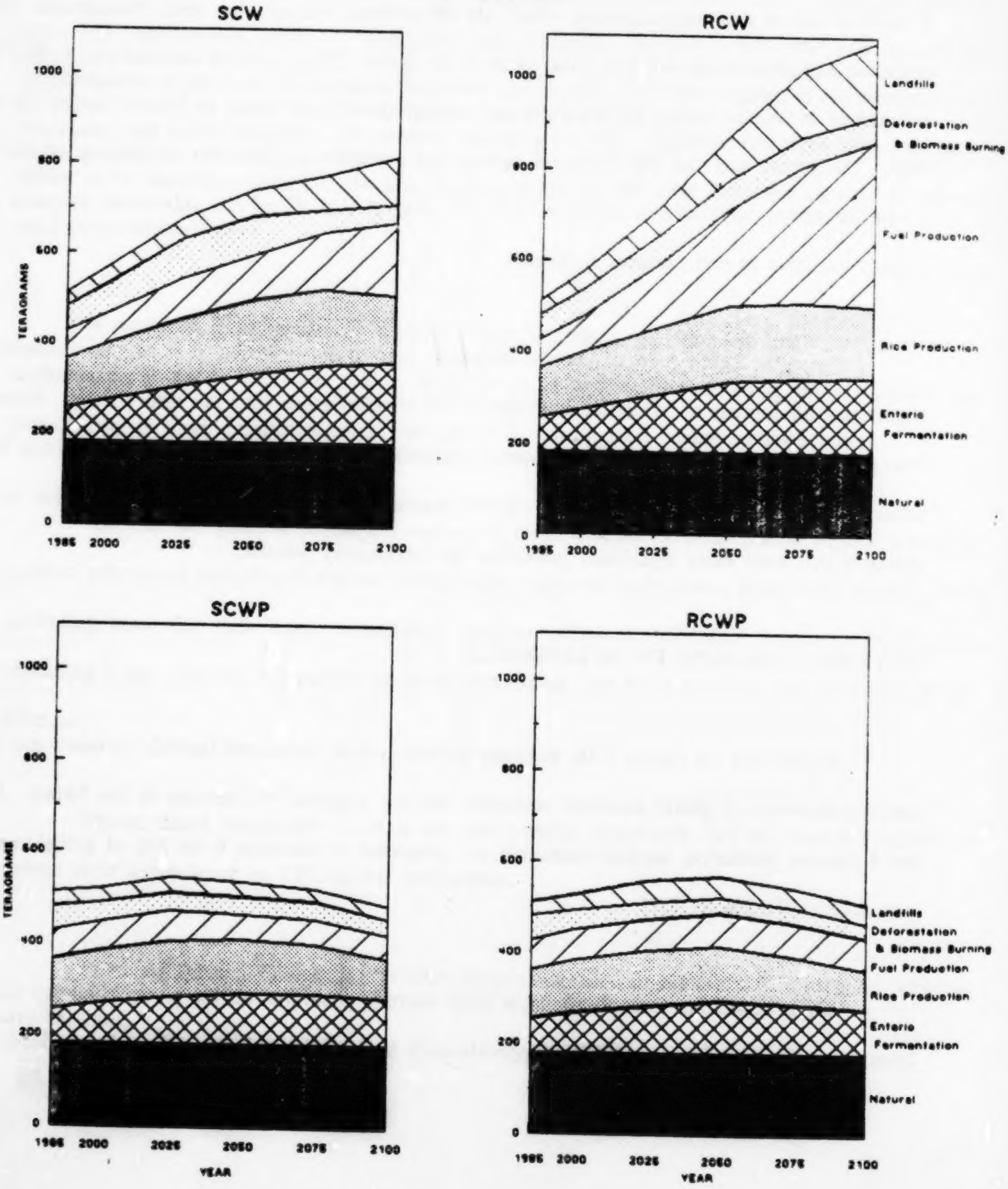
As indicated in Figure 7-18, methane emissions from municipal landfills currently are a very small component of global methane emissions but are expected to increase in the future. In the No Response scenarios, landfill emissions are projected to increase from 3% of global methane emissions to 7-8.5% by 2025.

Over 1.6 million tons of municipal solid waste is generated on the planet each day (adapted from Bingemer and Crutzen, 1987). Approximately 80% of this volume is disposed on land in

FIGURE 7-18

CH4 EMISSIONS BY TYPE

(Teragrams)



landfills or open dumps. Anaerobic decomposition of municipal and industrial solid wastes in landfills results in the generation of 30-70 Tg of methane each year (Bingemer and Crutzen, 1987).

The amount of gas produced by a given site is a function of the amount and composition of landfilled wastes. The rate of gas production is a function of the age of material in the landfill, oxygen and moisture concentrations, pH, and the presence of nutrients. Methane production is highest when the organic content of the refuse is high, the wastes are relatively new, and there is adequate moisture available. The decomposition process only occurs in an environment that is oxygen-free and has a moderate pH. There is a one- to two-year lag period between landfilling of wastes and the beginning of gas generation. Methane production occurs once all available oxygen has been consumed and the environment becomes anaerobic. Food and garden wastes generally decompose over a 1- to 5-year time frame, while paper wastes could require 5 to 20 years to decompose (Bingemer and Crutzen, 1987). These factors and the active life of a landfill affect the duration of methane production. It can take anywhere from 10 years to over 100 years for a landfill to produce significant amounts of methane (Wilkey et al., 1982).

Estimates place the rate of methane production between 1000 and 7000 cubic feet per ton (31-218 m^3/mt) of municipal solid waste deposited (Wilkey et al., 1982). The United States generated approximately 148 million tons of municipal solid waste in 1988 (U.S. EPA, 1988c), which, using the rates above, would produce between 2.9 and 20.7 Tg of methane. Using a methane production rate suggested by Bingemer and Crutzen (1987), the same amount of solid waste would produce an estimated 7 Tg of methane.[1]

---

[1] This estimate assumes a carbon content of 22% (Bingemer and Crutzen, 1987), that 90% of municipal solid waste generated is landfilled, and a conservative methane production efficiency of 0.25 ton of methane per ton of carbon.

Methane Recovery

Landfill gas, which is typically comprised of approximately 50% methane, 50% carbon dioxide, and some trace constituents of volatile organic compounds, can be recovered and used as fuel. The gas is a medium-Btu fuel (approximately 500 Btu/standard cubic foot), which can be used directly in boilers or for space heating, in gas turbines to generate electricity, or can be processed to high-Btu pipeline quality gas (Zimmerman et al., 1983). The gas is purified prior to use: for medium Btu-gas, processing requires removal of particulates and water; for high-Btu gas, carbon dioxide and most trace components must also be removed.

Landfill gas can present an environmental hazard because of its high combustibility and ability to migrate through soil. Methane is flammable in concentrations between 5 and 15% by volume in air at ordinary temperatures. Methane can rise vertically or can migrate horizontally out of a landfill. Methane migrates easily through porous soils, drainage corridors and other open areas, often to significant distances. Migrating methane gas has caused explosions and flash fires, resulting in property damage and death. Malodors and vegetative damage have also been attributed to migrating landfill gas.

Methane control systems, required under certain circumstances by the Resource Conservation and Recovery Act (RCRA), can help to mitigate malodors, gas hazards, and vegetative stress. RCRA requires that concentrations not exceed a lower explosive limit of 5% methane (10% landfill gas) at the landfill boundary. Controls include impermeable barriers, induced exhaust systems, evacuating and venting or flaring (burning) of the gas, and recovery for use as an energy source. Of these controls, only flaring and recovery of the gas reduce the amount of methane emitted into the atmosphere.

Of the 6,584 municipal solid waste landfills in operation in the U.S., 1539 (16.6%) employ some methane recovery or mitigation system such as venting or flaring. Only 123 of these sites (1.9% of total) recover methane for energy use (U.S. EPA, 1988c). New regulations proposed by EPA under the Clean Air Act would require collection and control of landfill gas at both new and existing landfills. These regulations have the potential to significantly reduce the emission of methane from landfills in the U.S. (U.S. EPA, 1988a).

Estimates place the quantity of gas generated by sanitary landfills in the United States at 1% of the nation's annual energy needs, or approximately 5% of current natural gas utilization (Escor, 1982). The recovery efficiency of methane from landfills can range between 60 and 90% of the gas produced, depending upon the quality and design of the gas recovery system, spacing of recovery wells, and landfill covering.

The economic viability of methane recovery at a landfill depends upon the landfill's size, location, proximity to potential users, current competing energy costs, and regulations governing the site. The capital costs of recovery projects are about $1000/kw. Suggested minimum requirements for recovery include an in-place refuse tonnage of 2 million tons, a disposal rate of 150 tons per day, an average refuse depth of 40 ft, a surface area of 40 acres, and two years of remaining active fill life (EMCOM Associates and Gas Recovery Systems, Inc., 1981).

It is probable that fewer than 1000 landfills in the U.S. are of sufficient size to meet these criteria. Sanitary landfills in developed countries hold the best potential for economical recovery of methane. Currently, there is little potential for methane recovery from open dumps in the developing world; if the practice of sanitary landfilling is adopted, the prospect of methane recovery will improve.

Over 408 (about 5%) of the municipal solid waste landfills in the U.S. receive more than 500 tons of municipal solid waste per day (U.S. EPA, 1988c). Collectively, these landfills receive over 75 million tons of municipal solid waste each year (over 50% of the total generated in the U.S.). If methane recovery were implemented only on the largest 5% of landfills in the U.S., an estimated 2.2-3.3 Tg of methane could be recovered.

Constraints on the economic feasibility of recovery projects have hampered further adoption of this technology. Under current market conditions, projects are not economically viable unless there is a suitable gas user within 2-3 miles of the site, or the electricity generation can be tied into an electricity grid. Current regulations governing many sites also discourage the recovery of methane. Some state regulations subject resource recovery projects to unlimited liability for any potential contamination problems at a landfill - a significant disincentive to recovery.

Various techniques can be used to enhance gas production and yield from a landfill, including controlled addition of moisture and nutrients (usually in the form of landfill leachate or landfill gas condensate), bacterial seeding, and pH control. The addition of leachate and condensate is only permitted at landfills where there is a liner. Further research in these areas could increase the economic viability of methane recovery.

Recycling and Resource Recovery

Recycling and resource recovery hold the potential to affect emissions of greenhouse gases through both waste reduction and reducing energy demand. Source separation and waste-stream reduction have many benefits for the municipality and the environment. A reduced waste stream means less refuse going to the landfill, an increasingly limited resource. In addition, the energy savings from recycling can be significant as discussed in **PART ONE: ENERGY SERVICES.**

Separating organics from the waste stream, such as paper and food, lawn, and garden wastes, can achieve many benefits, including reduced production of methane. Reducing organics in the landfill results in less methane production from that source. Organics that are separated and composted do not produce methane if the composting includes aeration to keep the process aerobic.

Within the industrialized countries of the OECD, garden and park wastes make up about 12-18% of the municipal solid waste stream and account for about 10-14% of its organic content, while food wastes make up between 20 and 50% of the stream and account for over 20% of the organic content. Within developing countries, garden and park wastes are insignificant, while food wastes account for between 40 and 80% of the waste stream and over 70% of the organic content (adapted from Bingemer and Crutzen, 1987). Given these high proportions of food, garden, and park wastes, the potential for reducing methane production through aerobic composting could be significant.

CO_2 Emissions From Cement Production

Carbon dioxide emissions from cement production originate from two sources: 1) as a chemical by-product of the manufacturing process, and 2) as a by-product of fossil fuel combustion used for kiln firing and plant electricity. Energy consumption emissions are discussed in the end-use section of this chapter. The CO_2 emissions that result as a chemical by-product occur during the firing process, when the raw materials (cement rock, limestone, clay, and shale) are exposed to progressively higher temperatures in a kiln. It is during calcination, which occurs at approximately 900 to 1000°C, that the limestone ($CaCO_3$) is converted to lime (CaO) and CO_2, and the CO_2 is released. For every million tons of cement produced, approximately 0.137 Tg C as CO_2 is emitted as a result of this chemical process (Rotty, 1987). For comparison, approximately 0.165 Tg C per million tons of cement produced result from energy consumption.

Although cement manufacture currently accounts for only a small percentage (approximately 2%, not including the energy consumption emissions) of the global anthropogenic source of CO_2, emissions associated with this industry have increased rapidly over the last few decades and can be expected to continue to grow in the future as demand for cement grows. Between 1950 and 1985, cement production and associated CO_2 emissions grew at an average annual rate of 6%. Regional production growth rates have varied during this period due to economic fluctuation in the construction industry (cement's primary market) and shifts in international competition between the cement-producing countries. Today, the USSR, China, Japan, and the U.S. account for 43% of the world's cement production.

Since CO_2 is an inherent product of cement manufacture, the only way to slow the rate of growth emissions is to limit the amount of cement required, i.e., reduce demand through more efficient use of cement and/or through substitution with other materials (e.g., steel and glass). Increases in efficiency can be achieved through both material and fabrication improvements, e.g., through the use of pre-stressed and steel-reinforced concrete products. Substitution of cement with other materials such as steel, glass or wood also would slow the growth in cement demand, although substitution with such energy-intensive materials as steel may result in greater net CO_2 emissions. In fact, in some applications cement products have been used in lieu of other materials, such as steel. Improved efficiency has already occurred in much of the developed world due to improved engineering design in construction. Also, most basic infrastructure has been built in the developed world, so demand may slow somewhat in the future. This is not likely to be the case in the developing world, however, where demand will probably continue to grow more rapidly than GNP, particularly since cement is an inexpensive building material.

PART FOUR: FORESTRY

FORESTS AND CARBON EMISSIONS

Forests, which store 20-100 times more carbon per unit area than croplands, play a critical role in the terrestrial carbon cycle (Houghton, 1988a). Active forest management to maintain high amounts of standing biomass, to reduce tropical deforestation, and to aggressively reforest surplus agricultural or degraded lands, offers significant potential for slowing atmospheric buildup of CO_2, N_2O, and CH_4.

The ecological diversity and geographic range of vegetation communities determine the degree of carbon sequestering by forests and the rate of carbon emissions due to disturbances of forests. Forests cover about one-third of the Earth's land, or 4 billion hectares, of which about 42% is in developed countries (mostly temperate) and 58% is in developing countries (mostly tropical) (FAO/WRI/World Bank/UNDP, 1987).[1] The carbon content of tropical moist forests (with closed canopies, like Amazonian rain forest) averages 155-160 t C/ha of standing biomass in Latin America and Asia and ranges up to 187 t C/ha in Africa.[2] The carbon content of dry tropical forests (open forests with grassy or herbal ground cover, as in African savannas) average 27 t C/ha in Latin America and Asia and 63 t C/ha in Africa (S. Brown, 1988b).

Anthropogenic alterations of forest ecosystems now account for emissions of atmospheric CO_2 equal to about 10-30% of total emissions from combustion of fossil fuels, as carbon stored in vegetation and soils is released by clearing, fire, or decay (Houghton, 1988a). Recent estimates of annual net carbon flux from deforestation range from 0.4 to 2.6 Pg C/yr for 1980, primarily due to land use change in the tropics (Detwiler and Hall, 1988a; Houghton et al., 1987).[3] Brazil, Indonesia, and Colombia are the largest of the top ten producers of net carbon release from tropical deforestation; these ten combined account for about half of the CO_2 emitted due to land use change (Houghton et al., 1987).

---

[1] hectare = 1 ha = 2.471 acres

[2] t C = tons of carbon.

Uncertainties still exist in determining carbon storage in and emissions from swidden (i.e., shifting, or slash and burn cycle) agriculture versus sedentary (permanent) agriculture, including agroforestry systems. Neither do we have reliable estimates of biomass, carbon content, and trace gas emissions in tropical forests (both standing and those being cleared) and carbon in disturbed tropical soils (about one-third of carbon flux from deforestation) (Houghton et al., 1988). Permanent conversion of natural forest to pasture or cropland results in net loss of carbon stored both in standing biomass and soils; the amount lost is dependent on the biomass productivity and soil carbon storage rates of the former versus the new land use. Cyclical harvest of forest for timber or fuelwood similarly releases carbon from slash (nonmarketable tree parts: branches, leaves) burned or left to decay on-site, and from timber milled into non-durable wood and paper products (and wastes like sawdust and scrap) that are soon burned or discarded.

Forests in temperate regions are essentially now in balance in terms of carbon cycling, with annual incremental growth rates roughly equal to rates of timber harvest and deforestation for urban growth and other land uses. Consequently, temperate forests do not currently contribute significantly to the increase in atmospheric CO_2 (Houghton et al., 1987). However, they now cover much smaller areas than in the past, and have historically contributed heavily to global carbon emissions, as forests were cleared in Europe and North America for agricultural production.

---

[3] Pg = petagram. 1 Pg = 10^{15} grams

Widespread reforestation programs that could expand temperate forests into former forest ranges and reduce net carbon emissions are discussed below. Trees newly planted in urban areas would alleviate the greenhouse problem in two ways: first by reducing the need for air conditioning and hence electricity, and second by increasing the uptake of carbon in biomass growth (Akbari et al., 1988).

DEFORESTATION

Each year, at least 11.3 million (and perhaps as high as 15 million, see below) hectares of forest are cleared in the tropics, an area larger than Austria or Tennessee (Lanly, 1982; IIED and WRI, 1987). The rate of deforestation -- combined with the escalating growth in demand for forest products -- is such that while 33 tropical countries are currently net exporters of wood products, this number may decline to fewer than 10 by the end of the century (Repetto, 1988). If this trend could be halted and reversed, tropical forests could serve as a vast carbon sink, reducing global CO_2 levels.

Figure 7-19 illustrates the movement of tropical forest lands among different stages of the deforestation cycle (an approach used by several researchers, e.g., Houghton et al., 1985; Lugo, 1988), and the conversion stages that the response options discussed below would address.

The underlying causes of deforestation vary widely by ecosystem and region, and are often complex, involving the interplay of historic, biological, economic, and political factors at both macro (national and transnational) and micro (household and village) levels. A recent international conference on the state of the world's tropical forests (Bellagio, 1987) concluded that:

FIGURE 7-19

MOVEMENT OF TROPICAL FOREST LANDS AMONG STAGES OF DEFORESTATION AND POTENTIAL TECHNICAL RESPONSE OPTIONS

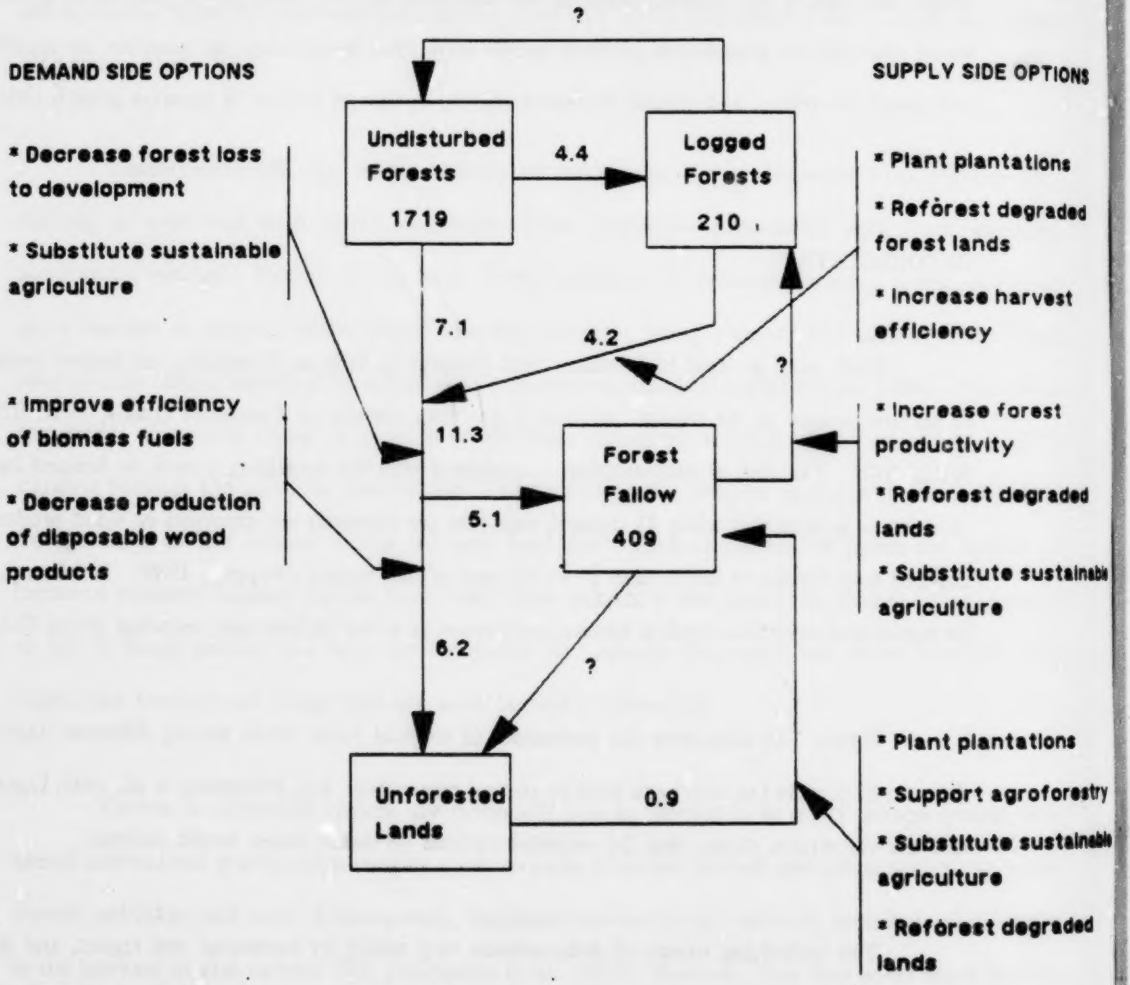

DEMAND SIDE OPTIONS
* Decrease forest loss to development
* Substitute sustainable agriculture
* Improve efficiency of biomass fuels
* Decrease production of disposable wood products
SUPPLY SIDE OPTIONS
* Plant plantations
* Reforest degraded forest lands
* Increase harvest efficiency
* Increase forest productivity
* Reforest degraded lands
* Substitute sustainable agriculture
* Plant plantations
* Support agroforestry
* Substitute sustainable agriculture
* Reforest degraded lands
Undisturbed Forests 1719
Logged Forests 210
Forest Fallow 409
Unforested Lands
?
4.4
7.1
4.2
?
11.3
5.1
6.2
?
0.9

Figure 7-19. Pathways of conversion of tropical closed and open forest lands, and where technical response options discussed here would intervene to slow conversion. Data were derived from FAO (1981) and from Lanly (1982), and are expressed in millions of hectares. Numbers inside boxes represent total area in category in 1980. Numbers on lines tipped with arrowheads represent annual rates of conversion. Data include both closed forests (complete canopy) and open forests (incomplete canopy and grass herbaceous layer). Source: Pathway data modified from Lugo, 1988. Houghton et al. (1985) offer similar conversion data.

> The causes of deforestation are well known. They include population pressure for agricultural land, the demand for industrial timber production and export, and inappropriate government policies regarding land tenure, economic incentives, forest settlement, and other population issues.

The predominate causes of deforestation vary by region. In tropical Africa and in South and Southeast Asia, rapid population growth appears to be the critical factor affecting deforestation. The majority of the population practices agriculture, and most of the increases in agricultural production necessary to sustain high birth rates have come from increases in the area under cultivation through deforestation. Seventy percent of Africa's deforestation stems from swidden (shifting) agriculture. Logging activities, both commercial and individual, in Malaysia, Indonesia, and the Philippines provide access to partially cleared forest lands that facilitates further clearing of forest for agriculture (Houghton, 1988a).

Rural populations rely on wood as the major source of energy, another important cause of deforestation. More than a billion people are currently affected globally by fuelwood shortages that cause them to spend much of their time searching increasing distances for wood to cook meals and heat homes. The fuelwood deficit in arid and semi-arid regions of the world in 1980 affected 29.3 million people, and totaled 13.1 million m^3 of wood. In the dry topics of Africa, the current annual rate of fuelwood consumption exceeds the annual rate of additions to supply through mean annual increment (growth of trees) by the following margins:

Sahelian countries (total):	30%
Sudan:	70%
Northern Nigeria:	75%
Ethiopia:	150%
Niger:	200%

This fuelwood gap between consumption and supply is anticipated to grow to 130% for the Sahelian countries overall by 2000, with single-country forecasts as high as 620% for Niger (Anderson and Fishwick, 1984).

The Amazon region in Brazil is experiencing one of the highest rates of tropical deforestation in the world (IIED and WRI, 1987; Fearnside, 1987). As a consequence, Amazonia is emitting greenhouse gases at rates and quantities high enough to affect global CO_2 and climate cycles. Yet due to the nature of centralized government policies regarding forests and development, the vast scale of its forest resources, and international pressures, Brazil offers high potential for slowing deforestation through proactive adjustments in government, commercial, and colonizing forest use and development practices. The problem is complex, however, as shown in Figure 7-20 which illustrates the complexity of deforestation pressures and consequences in Amazonia, and the implied difficulty of devising technical control solutions.

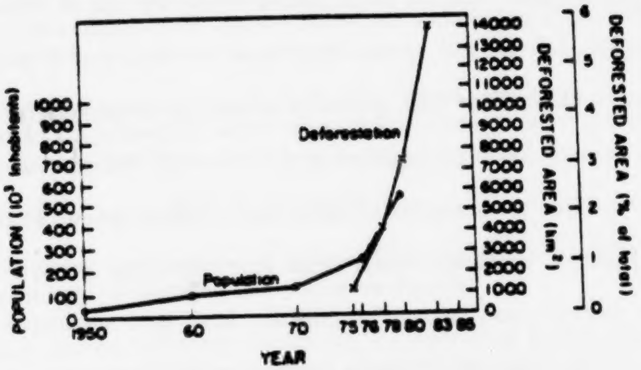
Brazil has 357 million hectares (ha) of closed tropical forest -- 30% of the global total, and three times as much as Indonesia, which is second to Brazil in its extent of forest area. Only 10% of the Atlantic coastal forest is left, mostly in southern Bahia; the rest has been lost due to logging and plantation clearing. The rate of deforestation in Rondonia doubled between 1976 and 1981, while the population increased 15% per year (Woodwell et al., 1986).

The situation in Brazil is changing rapidly. Analysis conducted at the Brazilian Space Research Center found that forest fires covered 20 million ha (77,000 square miles, or 1.5 times the area of New York state) during 1987, of which 8 million ha were virgin forest (Setzer and Pereira, 1988). This observation has forced reevaluation of standard mid-1980s estimates (e.g., Lanly, 1982) of 11.3 million ha deforested for the entire globe's closed and open tropical forests (Houghton, 1988b), and could raise estimates, perhaps as high as 15 million ha/yr for the late 1980s. The

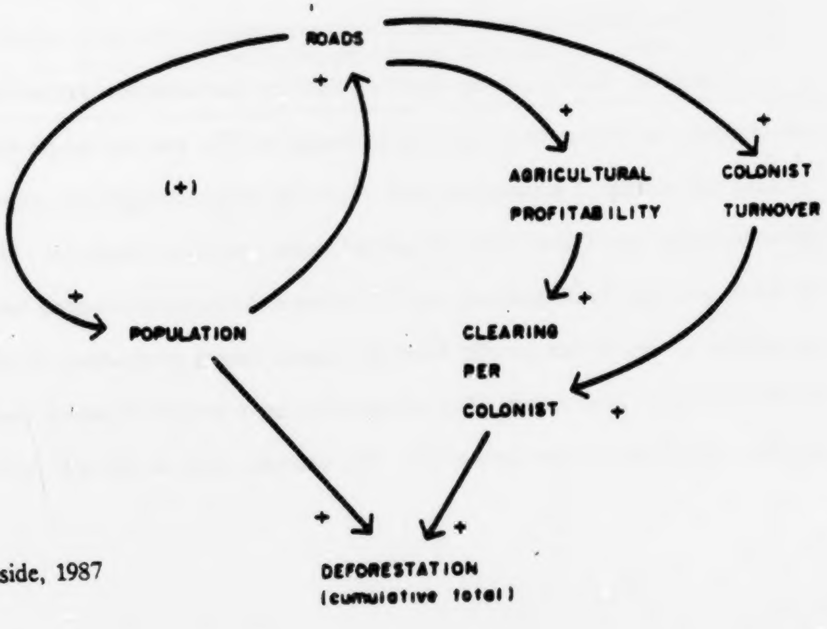
FIGURE 7-20

POPULATION GROWTH, ROAD BUILDING, AND DEFORESTATION IN AMAZONIA

A. Growth of population and deforested area in the state of Rondônia.



B. Causal loop diagram of the relationship between road building and deforestation.


ROADS
+
(+)
+
AGRICULTURAL PROFITABILITY
+
COLONIST TURNOVER
+
POPULATION
+
CLEARING PER COLONIST
+
+
+
DEFORESTATION (cumulative total)

Source: Fearnside, 1987

emissions from these fires contribute roughly 10% of total global emissions of CO_2 (Fearnside, 1985). If the Brazilian Amazon were completely cleared, 11 Pg of carbon would be released immediately, augmented by a continuing gradual release that would elevate the total to 62 Pg (Fearnside, 1985). Thus, deforestation in Brazil poses serious global consequences for climate change as well as the much discussed loss of species diversity.

In the Brazilian Amazon, major factors driving the loss of forests include land speculation, inflation, negative-interest and special crop loans, production of beef for export, and population redistribution in response to high growth rates and the mechanization of agriculture in southern Brazil. The Amazon has been perceived by entrepreneurs and planners as an undeveloped frontier capable of producing vast quantities of timber and minerals, and of absorbing underemployed urban populations from the southeast. Once roads have been built into the forest, land is worth more cleared than forested, and the profits obtained from land speculation are reinvested in further clearing (Fearnside, 1986, 1987; Maguire and Brown, 1986).

TECHNICAL CONTROL OPTIONS

Technical control options involving forestry can sequester carbon through the growth of woody plants, can reduce anthropogenic production of CO_2, and can complement other strategies for reducing the buildup of greenhouse gases. Forestry sector strategies for responding to the threat of global warming (see Table 7-13) basically fall under two broad categories: (1) Reduce the demand for forest land and forest products, and (2) Increase the supply of forested land and forest products. In addition to the obvious benefit, from the climate change perspective, of increasing the supply of forested land (i.e., trees absorb CO_2), afforestation has a number of valuable ecological and economic benefits worthwhile on their own merits. For example, more forests may provide jobs in the forest

TABLE 7-13
Major Forestry Sector Strategies for Stabilizing Climate Change

Reduce Demand for Forest Land and Forest Products

- Substitute sustainable, sedentary agricultural technologies for swidden (shifting) agriculture.
- Decrease consumption of forest for cash crops and development projects, through environmental planning and management.
- Improve the efficiency of biomass (fuelwood) combustion in cookstoves and industrial uses.
- Decrease the production of disposable forest products (e.g., paper, disposable chopsticks) by substituting durable wood or other goods, and by recycling wood products.

Increase Supply of Forested Land and Forest Products

- Improve forest productivity on existing forests, through management and biotechnology on managed and plantation forests.
- Increase harvest efficiency in forests, by harvesting more species with methods that damage fewer standing trees and use more of total biomass.
- Establish plantations on surplus cropland and urban lands in industrialized temperate zones, to produce high biomass and/or fast-growth species to fix carbon.
- Reforest degraded forests and establish plantations and agroforestry projects in the tropics, using both fast-growth and high-biomass species on short rotations for biomass and timber.

products industry, maintenance of biodiversity, watershed protection, non-point pollution reduction, and areas for recreation.

In the RCW scenario, a low rate of replanting is assumed and the area of tropical forests decreases exponentially from 1980 to 2100. (This assumption is the same as in Houghton, 1988b.) By contrast, the policy scenario (RCWP) assumes a rapid decline in deforestation (which ceases by 2015), and a linear increase in the establishment of plantations in the tropics. Implementation of the control options discussed below may make it possible to achieve the RCWP scenario, which results in a net CO_2 uptake of up to 0.7 Pg C/yr in 2025.

Compared with the annual crop cycles of agriculture, rotation time in forestry (the time necessary for one cycle of a forest crop to be planted, grown, and harvested) is slow -- typically on the order of 25-80 years in temperate zones and 8-50 years in the tropics (where growth rates are higher). Essentially, therefore, forestry climate strategies can create a net CO_2 sink for a fixed period, albeit long, since trees eventually die or are cut and release carbon through decay or burning. Harvesting on rotation (with aggressive replanting) allows storage of carbon in durable products like construction beams, crates, or fences, until they decay, and regeneration of new biomass at high rates of growth and carbon fixation.

All strategies listed in Table 7-13 could be pursued simultaneously. Some, however, are better suited to industrialized countries and some are more appropriate for developing countries. Strategies for maximizing both biomass growth rates and volume of standing stock are needed. Species that produce high volumes of biomass (e.g., Douglas fir in the Northwest) usually grow slowly (e.g., 80-100 years to mature) and are most useful in industrialized countries, whose conditions favor long-term forest protection and intensive management. Developing countries especially need to maximize biomass growth rates, to restore degraded and desertifying lands, and to produce fuelwood and timber. Developing countries face rapid forest depletion and high population growth rates, and have limited institutional capability to guarantee long forest rotation times in the face of these realities. However, developing countries should also plant high-value, long-rotation hardwood stands, and protect existing old-growth forests from cutting and burning.

All potential strategies, whether categorized as demand reduction or supply enhancement, to the extent feasible should be:

- sustainable over time, without deteriorating the natural resource base or introducing ecological changes (i.e., pests),
- capable of addressing the direct and indirect causes of forest loss by providing viable alternatives to current land use patterns,
- economically attractive (low-cost and offering income commensurate to present land uses),
- capable of providing an equivalent spectrum of forest products and jobs, at rates of return to labor (or time) and capital comparable to current forest use patterns,
- socially integrative or adaptive, building on local needs and tradition,
- technologically simple and durable, and
- readily adaptable to changing economic, political, social, and ecological realities (e.g., civil war, drought, and resource-driven population shifts).

In addition, these response options need to address the full range of causes of, and stages in, the rapid deforestation occurring in the tropics, including:

- logging and clearing by colonizers in closed canopy forests,
- fuelwood harvesting and swidden (shifting) agriculture in closed and open canopy forests,
- poor resource management of both undisturbed (virgin) and secondary (disturbed or fallow) forests,
- low reforestation planting and success rates on lands degraded by human resource use patterns (e.g., upland forests cut for timber and fuelwood and then overgrazed by goat and sheep herders).

See Table 7-14 for a summary of potential technical options for implementing forestry strategies to reduce demand and to increase supply.

Because of the long rotation times for forest growth, technical options will need to integrate short-term educational, harvesting, and research work with longer-term adaptations in forest planting, management, and product use.

Reduce Demand for Forest Land and Products

Both tropical and temperate forest lands are in high demand to provide a range of alternative land uses and forest products. Forests are consumed in areas of rapid population growth worldwide as villages and cities expand, transportation corridors are built to connect them, and additional arable land is sought for food production. Other major forces contributing to deforestation in the tropics, in particular, include swidden (shifting) agriculture; large-scale economic development projects (often financed by multilateral banks); cattle ranches and palm oil, timber, and rubber plantations; and fuelwood demand.

Based on population growth, projected demand for fuelwood by the year 2000 will require the creation of 20-25 x 10^6 ha (or perhaps as high as 50 million ha) of new closed forest plantations for fuelwood, at a cost of $50 billion, a rate 10-20 times current planting tallies (Nambiar, 1984; FAO, 1981; Lundgren and van Gelder, 1984). An additional 200 x 10^6 ha of croplands will be needed (FAO, 1978) just to maintain the already inadequate 1980 levels of per capita food supply.

Currently, more than ten hectares are lost to each one that is planted, based on the ratio of global deforestation to tree planting (Lanly, 1982). Models of forest product demand from 1980-

TABLE 7-14
Potential Forestry Strategies and Technical Options to Slow Climate Change

Strategy	Technical Options	Regions Most Effective In
Reduce Demand for Forest Land and Forest Products		
Substitute sustainable, integrated forest and natural resource management	• Natural forest management systems • Extractive reserves • Biosphere reserves	• Tropical moist and dry forests • Temperate forests (public or private)
Substitute sustainable agriculture	• Small-scale agroforestry • Financial incentives for swidden colonists to shift to sustainable practices • Technical aid in soil and crop selection • Plan into development projects by banks, state agencies	• Tropical moist & dry forests with strong central governments (Brazil, Colombia, Malaysia, Indonesia)
Decrease forest consumption for development	• Assistance from multilateral banks and state agencies contingent on planning. Loans contingent on minimal forest loss • Mitigation of loss by 2:1 protection of forest	• Strong central governments and banks with ability to plan and manage (Brazil, Costa Rica, India, China, Mexico)
Improve efficiency of biomass combustion	• Widely distribute efficient cookstoves • Incentives for industrial cogeneration	• Areas with inefficient current stoves, good extension, and difficult-access or expensive fuelwood (Nepal, India, Sahel, Haiti)
Decrease production of disposable forest products	• Substitute durable wood products for disposables • Establish recycling programs for wood	• Areas with cheap substitutes for wood & developed markets (industrialized areas of developing countries, Japan, U.S.)

TABLE 7-14 (Continued)
Potential Forestry Strategies and Technical Options to Slow Climate Change

Strategy	Technical Options	Regions Most Effective In
Increase Supply of Forested Land and Forest Products		
Increase forest productivity • Manage temperate forests • Apply natural forest management in tropics • Increase plantation productivity	• Intensify timber stand improvement all forests • Apply fertilizers & biotechnology to plantations • Extend natural forest management practices	• Developed countries and industrialized developing countries, with extension capability
Increase forest harvest efficiency	• Increase number of species harvested • Decrease damage to standing trees • Use harvest slash & mill scraps	• Any area, if marketed, and countries with large or multinational logging concessions (Brazil, Malaysia)
Plant trees on crop & urban lands in temperate zone • Expand tree planting programs • Reforest croplands • Reforest urban areas • Reforest highway corridors	• Reforest surplus cropland • Plant fast-growth plantations • Plant trees near buildings, highways, rivers	• Developed countries • US: Southeast, North Central states, West Coast
Reforest degraded forest lands and plant plantations in tropics	• Incentives for agroforestry • Establish extension farms & workers for agroforestry • Require commercial & village loggers to replant • Organize village tree planting • Mobilize youth and religious groups to plant trees	• Tropics, where rainfall and soils are adequate

2020 project tropical forest removals (harvest for timber) to double between 1980 and 2000, and then plummet to 72% of their 1980 level by 2020 (WRI et al., 1988; Grainger, 1987).

Option 1: Slow Deforestation by Introducing Sustainable Forest Use Systems

Net deforestation in an area results when demand for timber, fuelwood, or forested land exceeds the local supply and the productivity rates of forest lands allowed to regenerate do not keep place with the harvesting of products. One key method of reducing demand for virgin or secondary forest is to introduce sustainable natural resource management techniques at the village and regional levels that provide a stream of forest benefits but minimize cutting of natural forest. McNeely (1988) and McNeely and Miller (1984) offer theory and case studies illustrating the economics of non-consumptive, integrated natural resource management.

Natural forest management (NFM) applies silvicultural techniques to allow smaller sustainable harvests of natural forests, instead of traditional clear-cuts of large tracts to maximize short-term profits. NFM may increase forest productivity, and provides a wide range of non-wood products with high economic returns (e.g., nuts, herbal medicines, nature tourism operations; see Gradwohl and Greenberg, 1988). Extractive reserves are a newly evolved example of NFM in which economic products like nuts and rubber are extracted from forest reserves in Brazil. They maintain standing forest while providing jobs and wages to organized rubber tappers and nut collectors otherwise dependent upon income from logging (Schwartzman and Allegretti, 1987).

The Malaysian Uniform System is a 60-year NFM rotation technique developed to rapidly regenerate harvested dipterocarp forest (lowland closed forest dominated by trees of the Dipterocarpaceae family) in peninsular Malaysia. Another method is the Celos Silvicultural System, practiced on long-term research plots in Suriname, which uses carefully planned logging trails and winches to reduce damage to standing trees during harvest from 25% down to about 12%. Numerous small areas are cut on 20-year rotations, rather than single huge tracts, and 3 improvement thinnings of non-target tree species and vines are made each rotation.

The Palcazu Development Project in Peru, funded by the U.S. Agency for International Development, has devised a system of active forest management that harvests thin swaths of forest 20-50 meters wide on 30-40 year rotations. Old-growth forest left surrounding the strips naturally provides seed dispersal after harvest, as in natural tree-gap regeneration processes, and maintains biological diversity lost in logging operations. Potential net profits after the wood is processed could be as high as $3500/ha worked, according to estimates by researchers (Hartshorn et. al, 1987).

NFM systems could be widely introduced via forest extension programs, bilateral and multilateral rural development projects, and integrated management of protected reserves and adjacent lands (e.g., the Biosphere Reserve concept of multiple-purpose protected areas combining preservation, research, and economic use zones [McNeely and Miller, 1984]). NFM offers a promising vehicle for maintaining high-biomass standing forest, slowing deforestation, and allowing the 54 million ha of forests already logged (WRI and IIED, 1988) to regenerate.

Option 2: Substitute Sustainable Agriculture for Swidden Forest Practices

Sustainable agricultural systems are those that rely on biological recycling of chemical nutrients (in soils) and energy, and on naturally occurring mechanisms for protecting crops from pests, to produce annual harvests that can be sustained in perpetuity (Dover and Talbot, 1987). Generally such systems use low levels of agricultural technology (i.e., minimal agricultural pesticides or fertilizers or improved seeds, and few conservation measures).

Sustainable agriculture offers three major types of benefits for the carbon cycle:

- increased supply of woody biomass fixing carbon in natural forests and in forest-crop systems.
- reduced demand for natural forest wood products, and
- reduced demand for new land cut from primary or secondary forest for swidden agriculture (by substituting higher-nutrient sedentary systems on permanent plots).

Other non-carbon-cycle benefits of sustainable agricultural systems include the preservation of biological diversity, low soil erosion, maintenance of the hydrological cycle and soil moisture, and recreation and tourism.

Swidden (or shifting) agricultural methods involve cutting and, usually, burning forest patches, to plant crops that are harvested for 1-7 years, and then abandoning and leaving fallow the patches for about 7-14 years as new patches are cut and farmed. About 41 million ha of tropical primary and secondary forest are burned per year (see Chapter IV). Tropical forests store up to 90% of a plot's nutrients in woody plants (compared with temperate forests, where only 3% are stored in plants and 97% in soils), some of which are released by burning (Keay, 1978). Swidden systems persist throughout the world, especially in remote and hill districts, and during times of individual or regional economic stress. On Negros Island in the Philippines, the number of swidden farmers rose by 80% in only two years in the mid-1980s because of declines in the sugarcane industry that forced underemployed workers into swidden agriculture to grow food. Ecologists predicted that a major rain forest there could be destroyed by the year 2000 (Dover and Talbot, 1987).

Sustainable agriculture and soil management systems can be introduced as a substitute for swidden systems that require destruction of virgin or secondary forest. For every hectare farmers put into such methods, 5-10 hectares of tropical rainforest may be saved from destruction to store carbon, conserve hydrologic cycles, and retain biological diversity, according to Sanchez (1988). Table 7-15 shows the equivalent area of forests needed for traditional swidden practices for every one hectare of forest land needed for more resource-intensive sustainable uses with higher productivity rates. Agroforestry is the combination of agricultural and forestry techniques to produce woody plants on the same parcels as food or commodity crops or animals, with a mutually beneficial synergism. It

TABLE 7-15

Comparison of Land Required for Sustainable Swidden Versus Agricultural Practices

Sustainable Agricultural Practices	Number of Swidden Hectares Required for Every One Hectare of Sustainable
Flooded rice	11.0
Low-input cropping (transitional)	4.6
High-input cropping	8.8
Legume-based pastures	10.5
Agroforestry systems	not determined

Source: Derived from 17-year ongoing research by North Carolina State team at Yurimaguas, Peru, in tropical moist lowland forest (Sanchez, 1988, and Sanchez and Benites, 1987).

offers one of the most promising approaches to providing both fuelwood and food needs, while reducing environmental externalities associated with monocultural row cropping (pesticide use, pest population surges, high irrigation requirements). Interest in agroforestry has surged since the late 1970s, and international research and project lending is underway in approximately 100 developing nations.

Agroforestry systems derive from traditional forest farming practices of many indigenous peoples and are sustainable over long rotations, large acreages, and low population densities. Innovative research programs should build on these local methods, where feasible. The Lacandon Maya Indians living in rainforest in Chiapas, Mexico, practice a multiple-layer cropping system utilizing up to 75 species in 1-hectare plots that produce crops for 5-7 years. As soil fertility wanes, the Lacandon plant tree crops (cacao, citrus, rubber, avocado) that provide valuable products as the plots regenerate with secondary forest. This forest is cut again when the trees overgrow the managed species. It is estimated that only 10 hectares of rain forest are consumed per farmer throughout his career with this method of sustained agroforestry. In contrast, immigrant colonists consume two or three times as much forest area (Nations and Komer, 1983).

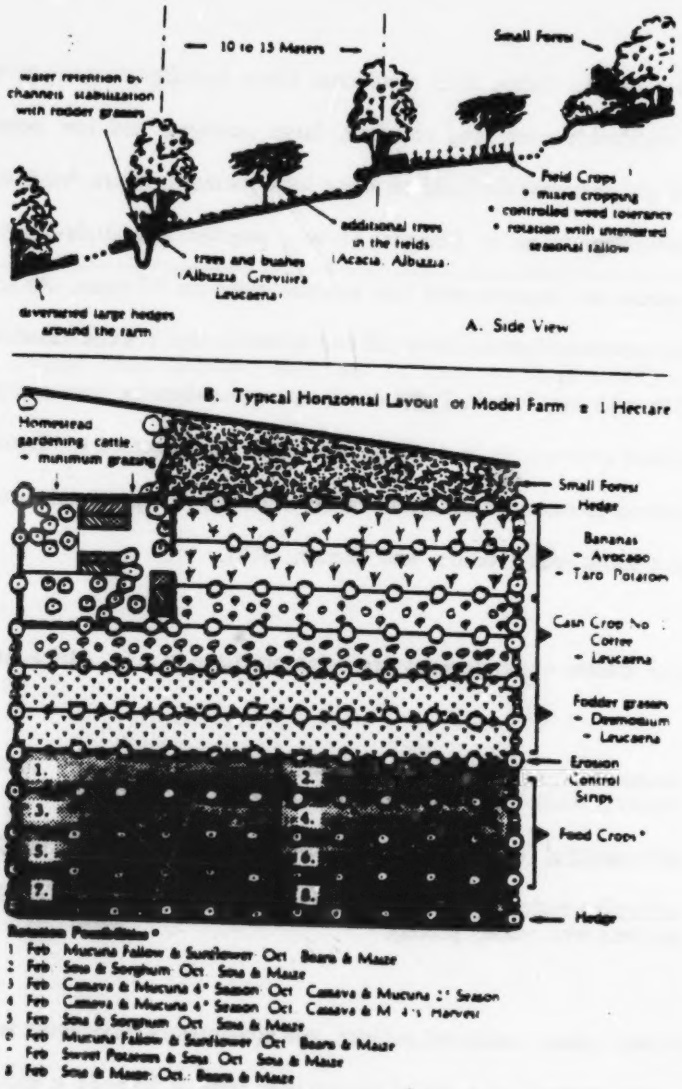
Three major classes of agroforestry are being practiced in Asia, Africa, and Latin America:

1. agro-silvicultural (including fuelwood trees, hedgerow or "alley" intercropping, Taungya forestry, shelterbelts and windbreaks),
2. silvo-pastoral (fodder production, living fences, trees in pastures), and
3. agro-silvo-pastoral (woody hedges for grazing by livestock and producing mulch, home gardens with woody plants).

Other systems include traditional swidden, and aquaforestry (silviculture in mangrove swamps and fish ponds). One example of a model agroforestry farm in Rwanda is illustrated in Figure 7-21, incorporating trees and bushes in erosion-control strips, hedges, nitrogen-fixing trees in fields, and cash and fodder crops (Dover and Talbot, 1987). (Further information on the array of systems is

FIGURE 7-21

MODEL AGROFORESTRY FARM LAYOUT, RWANDA


10 to 15 Meters
Small Forest
water retention by channels stabilization with fodder grasses
Field Crops
• mixed cropping
• controlled weed tolerance
• rotation with intercalated seasonal fallow
additional trees in the fields (Acacia, Albizzia)
trees and bushes (Albizzia, Grevillea, Leucaena)
diversified large hedges around the farm
A. Side View
B. Typical Horizontal Layout of Model Farm ≥ 1 Hectare
Homestead gardening, cattle, • minimum grazing
Small Forest
Hedge
Bananas
• Avocado
• Taro Potatoes
Cash Crop No. 1 Coffee
• Leucaena
Fodder grasses
• Desmodium
• Leucaena
Erosion Control Strips
Food Crops*
Hedge
1. 2. 3. 4. 5. 6. 7. 8.
Rotation Possibilities*
1 Feb Mucuna Fallow & Sunflower Oct Beans & Maize
2 Feb Soja & Sorghum Oct Soja & Maize
3 Feb Cassava & Mucuna 4° Season Oct Cassava & Mucuna 2° Season
4 Feb Cassava & Mucuna 4° Season Oct Cassava & M 4's Harvest
5 Feb Soja & Sorghum Oct Soja & Maize
6 Feb Mucuna Fallow & Sunflower Oct Beans & Maize
7 Feb Sweet Potatoes & Soja Oct Soja & Maize
8 Feb Soja & Maize Oct. Beans & Maize

Source: Dover and Talbot, 1987, derived from Behmel and Neumann, 1981 available in Winterbottom and Hazelwood, 1987; Dover and Talbot, 1987; Winterbottom et al., in press; and OTA, 1984).

Integrated crop-forest systems not only reduce demand for forest, but also retain carbon stored in tropical soils (otherwise emitted after disturbance), and in woody biomass, although at rates well below mature forest. A typical agroforestry system in steep uplands with poor soils in Himachal Pradesh, India, is stocked with 20.5 trees/ha, which produce a yield of 2.0 m^3/ha/yr of wood, or 0.8 t C/ha/yr, plus the potential savings of roughly a 5:1 ratio of ha of virgin forest retained intact per ha converted to permanent cultivation. A more intensive stocking rate of 322 trees/ha in home gardens in Surakarta, Indonesia, yields 7.3 m^3/ha/yr wood, or 1.9 t C/ha/yr. Data from Indonesia and Tanzania indicate that 200-300 trees are sufficient to provide wood-production needs of a typical household (Lundgren and van Gelder, 1984).

Reliable estimates of global acreage with potential for substitution of agroforestry for swidden agriculture, and net carbon benefits, are not presently available. Preliminary calculations for an integrated agroforestry and plantation project in Guatemala designed for an American utility (AES) to offset its CO_2 emissions are offered by Trexler (in press) and outlined in Table 7-23. An overview of potential carbon cycle and biomass productivity benefits from a range of agroforestry systems is presented in Table 7-16.

Agroforestry projects considered successful from a climate change perspective would require suitable environmental conditions (soils and rainfall), and human population densities and institutions adequate to encourage multi-year resource management. Either overcrowding or pervasive poverty will shift the focus to short-term survival. Social and economic factors likely to promote success include clear and relatively equitable land tenure for farmers; local decision-making, and political systems that at least tolerate medium-term investment by villagers of various classes; developed and accessible markets for crop and forest products; and adequate protection of agroforestry systems

TABLE 7-16

Potential Carbon Fixation and Biomass Production Benefits from Agroforestry Systems

Type of System	Location	Trees Per Hectare	Productivity (t C/ha/yr)	Species Used	Products Produced
Natural forest management and crops	Guesselbodi forest, Niger		0.8	native shrubs (*Combretum micranthum*, *Guiera senegalensis*)	wood, mulch, crops, gums, fodder, medicines
Steep uplands, poor soils system	Himachal Pradesh, India	20.5	0.8		fuelwood, fodder, crops
Alley cropping	IITA, Nigeria		0.9-3	nitrogen-fixing shrubs (*Glicidia*, *Leucaena*, *Calliandra*, *Sesbania*)	maize in alleys between hedgerows cut for mulch and stakes
Home gardens	Surakarta, Indonesia	322	1.9		fruit, fodder, mulch fuelwood
CARE Agroforestry and Resource Conservation Project	Guatemala	400	4.7	conifers (highlands), hardwoods (lowlands). 20 species in total	fuelwood, fodder, crops

Source: Winterbottom and Hazelwood, 1987, and WRI et al., 1988 (Niger, Nigeria); Lungren and van Gelder, 1984 (India, Indonesia); Trexler, in press, and WRI, 1988 (Guatemala).

from grazing livestock, villagers, civil strife, and rapid economic changes (Winterbottom and Hazelwood, 1987; IIED and WRI, 1987).

Constraints to wide diffusion of agroforestry include the difficulty of technology transfer to remote populations often holding traditional values that do not encourage innovation; the need for systems tailored to specific site conditions; capital requirements to purchase and maintain seedling nurseries and to fund extension efforts and research; and the vast scale of implementation necessary to slow forest degradation (Lundgren and van Gelder, 1984). The long-term sustainability of new agroforestry systems has not been fully demonstrated in many first-generation projects, which often still rely upon high levels of fertilizer and labor.

Option 3: Reduce Demand For Other Land Uses That Have Deforestation As A Byproduct

Large development projects, especially those planned in the tropics by transnational corporations and multilateral development banks, consume huge tracts of forest for roads, hydroelectric project reservoirs, and new communities. The Mahaweli project in Sri Lanka will destroy 260,000 ha of tropical moist forest in order to generate 466 MW of electric power and flood control and irrigation benefits. The Narmada Valley Project in Madhya Pradeshi, India, may inundate 350,000 ha of teak and bamboo forest (Kalpavriksh, 1985).

Pressure on banks and governments to reduce adverse impacts on tropical forests has mounted since 1980 and spawned new development planning methods that include protection of forest tracts, in order to offset consumptive use of other forested lands (Rich, 1989; Gradwohl and Greenberg, 1988). In 1986, the World Bank issued a 6-element new policy on wildlands to guide planning of Bank development projects. This policy states preference for choosing already degraded (e.g., logged over) and the least-valuable lands for development purposes. It requires compensation for wildlands converted by Bank projects, in the form of an added wildlands management and preservation component (Goodland, 1988; World Bank, 1986). India is experimenting with compensatory reforestation, at a 2:1 replacement ratio, for forest cut for hydro projects, although problems still remain with such mitigation approaches -- including management responsibility over long time frames, and potential productivity rates of new compensatory forests.

Option 4: Increase Conversion Efficiencies Of Technologies Using Fuelwood

Fuelwood demand from tropical forests accounts for significant deforestation. Wood supplies over 90% of total energy use in Burkino Faso, Malawi, Tanzania, and Nepal; 50% in Indonesia; 25% in China; and 20% in Brazil (Brown et al., 1988a). Annual average fuelwood consumption for agricultural and industrial uses in Tanzania from 1979-80, for example, consumed 1.9×10^6 m^3 of fuelwood, releasing 0.5×10^6 t C, to cure tobacco, smoke fish, dry tea, fire pottery, and burn bricks (Mwandosya and Luhanga, 1985).

The introduction of more efficient cookstoves and industrial technologies could reduce wood requirements by 25-70% at very low cost (Goldemberg et al., 1987; Brown et al., 1988a), as discussed in the energy section of this chapter. The most successful strategy for reducing fuelwood-related deforestation in the long run may be the substitution of kerosene, gas, and electricity for fuelwood, and widespread distribution of cogeneration technologies to produce higher benefits from fuelwood use.

Option 5: Decrease Production of Disposable Forest Products

Forests harvested in developing countries or managed in industrialized nations to generate wood products that are consumed and then burned or buried in landfills in the short term (e.g., newsprint, paper goods, and fast-food packaging) contribute greenhouse gas emissions. Work has begun on introducing technologies and programs to replace consumable forest products with durable goods that are used repeatedly and/or recycled, avoiding these emissions and providing carbon storage. Two major control options are discussed below.

Substitute durable wood or non-wood products for high-volume disposable uses of wood

Current storage of durable wood products has been estimated at about 10 x 10^9 m^3 of solid wood (2.6 Pg of carbon), or roughly 25% of world industrial harvest over the past 35 years (Sedjo and Solomon, in press).

The global forest industry has been stagnating for the past 15 years, as real prices have decreased, growth in consumption has shrunk, and competition on world markets has accelerated from developing countries. FAO (1986a) and Kuusela (1987), however, project annual growth rates of wood-based panels for 1985-95 at about 2.5-4.0%, down from 6.9% in 1963-75, but along with printing and writing paper the most quickly rising rate. Total world production of principal forest products for 1978-82 averaged 805.5 x 10^6 t/yr, or about 0.4 Pg C/yr, and is projected to rise to a mean estimate of 1333 x 10^6 t/yr (0.66 Pg C) by 2000.

Accelerated harvest and storage of wood products could provide a technical response option for reducing demand for products from virgin forest, and increasing supply from managed forests. For example, if production of all wood products was increased by 30% on average above the projected growth from 1982-2000, and this increase occurred through increased use of durable wood products, then production would rise to 1733 x 10^6 t/yr, storing an additional 0.4 Pg C over the 18-year period. Potential storage over the next 50 years to 2030 has not been calculated, but might reach a total of more than 1 Pg C.

Examples of potential product shifts from consumables to durables include eliminating the use of disposable chopsticks in Japan and elsewhere, in favor of permanent wood or plastic ones; replacing single-use wooden crates for shipping, fruit and pallets with metal or plastic ones; and widely installing wood paneling in homes and commercial structures. To achieve net greenhouse gas emission benefits, production processes for durables must minimize generation of gaseous byproducts through use of energy conservation measures noted earlier in this chapter.

Expand recycling programs for forest products

Global production of newsprint, paperboard, and other paper averaged 334 million t/yr from 1978-82, with growth rates to 2000 anticipated to hover around 3% per annum (FAO, 1986a,b).

In the U.S., consumption of all paper products in 1988 totalled 79.8 million tons. Post-consumer recycling of paper in the U.S. now provides 28% of domestic production of paper and paperboard, and totaled about 22.3 million tons in 1986 -- virtually twice the amount recycled in 1970 (U.S. EPA, 1988). Current obstacles to enhanced recycling rates include market development, regulatory, and financial issues (Ruston, 1988).

Recycling of paper products in the U.S. could be pursued as a climate change response option. If, for example, recycling rose to 80% (with 10% diverted to (stored in) durable books or construction, and 10% disposed of), then the difference between the number of tons burned or buried in landfills in 1986 at 28% recycling (about 50 million tons) and at an 80% rate (about 16 million tons) would equal 34 million tons/yr. Methane production from landfills (see Landfills section, this chapter) and carbon emissions from incineration would decline. Paper products formerly treated as consumables would become converted to essentially durable recycled products, thereby increasing the net total stock of carbon (assuming that forests previously used to grow wood for paper remain undisturbed).

Increase Supply of Forested Land and Forest Products

Option 1: Increase Forest Productivity: Manage Temperate Forests For Higher Yields

Modern forestry management techniques applied to commercial, state, and large private forest lands offer the greatest potential for large-scale increases in productivity.

In the U.S., new forest area growing at average rates would not be sufficient to offset our current annual production of 1.3 Pg C. Per capita annual carbon production for 237 million Americans is about 5 t C/capita. U.S. commercial forests (those producing greater than 1.4 m^3/ha/yr and not set aside in parks) totalled 195.3 x 10^6 ha in 1977, with a net average growth rate of 3.15 m^3/ha/yr, or 0.82 t C/ha/yr. Thus, 6 ha (15 ac) of forest would be required to sequester each person's fossil fuel emissions. For 237 million people this would require 1.5 x 10^9 ha of average forest -- a tract 50% larger than the 0.9 x 10^9 ha land area of the country (Marland, 1988).

However, intensive forest management to increase biological productivity or economic returns on forest land may offer a partial solution. The U.S. Forest Service (USFS, 1982) estimates that if current commercial forests simply were fully stocked (i.e., they were universally managed to grow the tree densities and volumes of mature stands), their net annual growth could be increased by about 65%, which would sequester 0.1 Pg C/yr. This full stocking option is appealing, since many areas not presently growing forests are sites so poor that even intensive management or aggressive planting are likely to provide only negligible net annual growth (USFS, 1982). Forest Service estimates also indicate that forest owners could go further by managing forests to take advantage of economically feasible opportunities that would offer a 4% annual return on investment. These management options could produce an additional 18 billion cubic feet of annual forest growth, equal to 0.16 Pg C (327 x 10^6 t wood) (Hagenstein, 1988; Moll, 1988).

Intensive management techniques that improve productivity include site-specific species selection (through provenance trials with seeds), thinning and release cuttings, control of spacing among trees, weed and pest control, fire suppression, fertilization, irrigation, and planting genetically improved seedlings. All options requiring significant labor tend to be prohibitively expensive if implemented on large scales; however, access to volunteer labor from youth or citizen groups might make these options more feasible.

The economics of fertilization on large tracts vary; for many species and sites, the costs of chemical fertilizers exceed growth stimulated. Yet according to Ford (1984), "fertilization is the most important single treatment that the forest manager can apply during the growth of the crop to accelerate growth." More than half of the loblolly pine plantations in the Southeast would show value-added growth from fertilization, according to one observer (Binkley, 1986).

Obstacles to use of fertilizers include trees' low nutrient recovery rates, due to leaching and microbial activity; the nutrient status of the site; and whether slash is removed from the site during harvest (tropical forests store 90% of available nutrients in biomass and only 10% in soils, compared with about 30% for temperate forest biomass) (Marland, 1988; Ballard, 1984). Nitrogen-fixing legume species, like black locust and honey locust in the U.S. and *Leucaena* and *Calliandra* in the tropics, offer the advantages of supplying their own nutrient requirements, growing well in the depleted soils of degraded lands, and cutting fertilizer costs.

Other constraints to intensive management include the need for very short rotations to maintain high growth rates (and associated labor costs and need to sequester large volumes of harvested wood); pest and genetic diversity problems associated with monocultural stands; costs of energy and labor for plantations; the tradeoff between maintaining large volumes of standing biomass and fast growth rates; and fire management costs.

Option 2: Increase Forest Productivity: Improve Natural Forest Management of Tropical Little-Disturbed And Secondary Forests

Natural tropical moist forests produce annual wood increments higher then managed forests on average (Table 7-17), due to the latter's higher harvest offtake volumes, minimal replanting success, and reduced biomass in regenerating forests. From a carbon-cycle perspective, this offers an argument in favor of a two-prong forest management strategy managing virgin and secondary forests as sustainable high-biomass sinks, and managing fast-growth plantations for provision of

TABLE 7-17

Natural and Managed Tropical Moist Forest Yields
(mean annual wood increment, metric tons per hectare)

Continent	Unmanaged Forest[1]	Managed Forest
Africa	2.3-5.8	0.6-1.3
Latin America	0.9-1.9	0.6-2.0
Asia	3.7-4.5	1.3-2.6

[1] Unmanaged forests are stands in balance, where annual increment roughly equals forest losses from natural causes.

Source: IIED and WRI, 1987 (from Wadsworth, 1983).

forest products. Natural forest management (NFM) techniques (discussed under demand option 1, above) can generate products and services that sustain indigenous and village populations otherwise engaged in forest felling, and serve as high-biomass carbon sinks. Natural forests comprise 83% of the tropical forest under intensive management, on 35 million ha; only 7.07 million ha of intensively managed tropical forests have been planted or artificially regenerated (IIED and WRI, 1987). Hence, NFM, while requiring considerable investments of labor, may present the most viable long-run option for forestry in the vast majority of tropical forest lands.

Multiple-use management employs timber harvesting, replanting, stand improvement (release cutting), and forest protection to confer benefits from timber sales, recreation, and flood control. Fully 16% of tropical moist forest species have non-timber economic benefits, according to one recent survey by IUCN (IIED and WRI, 1987). Minor forest products like rattan, latex, resins, medicinal plants, and bamboo contributed $150 million to Indonesia's economy in 1982 (Repetto, 1988).

Option 3: Increase Forest Productivity: Plantation Forests

Plantation biomass productivity can be improved by three types of actions:

1. silvicultural practices that yield biomass gains, especially in industrialized country forests;
2. lengthened and stabilized land tenure for commercial and community forestry projects in developing countries, to encourage forest management for multiple (rather than single) rotations and the ensuing environmental benefits; and
3. biotechnology advancements utilizing genetics and seed selection.

This discussion focuses primarily on biotechnology and genetic potential, as silvicultural management is addressed below, and land tenure considerations reside in the realm of policy.

Plantations managed to grow a mix of short, medium, and long-rotation species, if site conditions allow, are most likely to provide the continuous stream of forest products and income necessary to meet timber and fuelwood demand in developing country villages. Similarly, mixed-stand (multiple species) plantations in temperate zones may reduce ecological problems (e.g., pest infestations) and timber market disruptions, although mixed-stand plantations may require more intensive management and harvest techniques.

Applied genetics or tree improvement may produce greater increases in yields of biomass than improved silvicultural methods. Short-rotation intensive culture (SRIC) efforts apply intensive agronomic practices to growing selected and/or genetically improved hardwood species in plantations, to achieve maximal productivity rates at competitive costs. The Department of Energy's Short-Rotation Woody Crops Program, begun in 1977, has conducted field trials to boost productivity and reduce costs of woody species managed under SRIC as an energy source. Its target is to achieve average productivity of 20 dry t/ha/yr (10 t C/ha) of biomass at a cost of $2.25/GJ on optimal plots by 1995, and a competitive technology 5 years later.

By 1987, productivity reached 13 dry t/ha/yr (6.5 t C/ha), at a cost of $55/dry t, or $3.25/GJ (ranging from $2.90 to $5.10 delivered), on SCS site class I-III soils (i.e, largely fertile and flat). Planting densities ranged from 2500-4000 trees/ha, on coppice rotations of 5-8 years. Ongoing research is focused on 4 species (silver maple, sweetgum, American sycamore, and black locust) and one genus (*Populus*, including cottonwood, poplar, and aspen). Collectively, average SRIC growth rates have reached about 9.5 dry t/ha, or 4.7 t C/ha. Rates as high as 12-14 t C/ha have been documented for exotic or hybrid trees (Ranney et. al., 1987).

Other species with high potential for plantation biomass production include wood grass (*Populus*), grown at densities of about 1700 trees/ha for 4-year rotations, and 25,000/ha for 2-year rotations (Shen, 1988). Kenaf, an African annual crop closely related to hibiscus, grows to 6 meters in 120-150 days after seeding, and can produce 3-5 times more pulp for paper than trees, on an annual basis, potentially freeing forests for biomass production and carbon storage. Field trials in Texas by the Department of Agriculture have found that kenaf grows well without pesticides in the

Cotton Belt and with irrigation in the drier Southern states, and requires less chemical input than wood to produce and whiten pulp. Ninety percent of its original weight can be converted to usable fiber (Brody, 1988).

Working with tropical species in Espirito Santo, Brazil, Aracruz pulp company has produced eucalyptus hybrids with 30% increased height and 80% improved diameter at breast height (dbh) over parents at 4 years, through selection of parent tree seeds, breeding for desired characteristics, and planting into specific microsites. Average yields of 70 m^3/ha/yr (18.2 t C/ha/yr) for 14 million trees per year grown from rooted cuttings of 54 species have been achieved, and yields of 100 m^3 (26 t C) or greater are projected. Stands are managed for bleached pulp and charcoal for steel making. The trees reach 20 meters in height in less than three years (OTA, 1984; IIED and WRI, 1987). Other trials with eucalyptus from 32 sites in 18 countries have generated productivity gains of several hundred percent simply by matching optimal seed characteristics with site soil and microenvironmental conditions (Palmberg, 1981).

Pine breeding for straightness, reduced forking, and drought resistance, coordinated by seed cooperatives in Latin American and Europe, are showing significant improvements. Other tree-improvement methods include seed orchards relying on grafting and rooted cuttings that produce clones of trees, but these methods are limited to only a few species. Tissue culture (manipulating sprouts from germinating seeds) is still in its infancy in forestry, although the Weyerhaeuser Corporation in the U.S. Northwest plans soon to produce 100,000 clones of Douglas fir per year. Research on producing cell culture embryoids (microscopic infant trees) is underway in major developed countries on temperate species, and early work on teak and Caribbean pine is encouraging (IIED and WRI, 1987).

Table 7-18 surveys productivity increases from intensive management and applied genetics for selected species in the U.S. and in the tropics.

TABLE 7-18
Productivity Increases Attributable to Intensive Plantation Management

Management Technique	Maximum Mean Annual Yield (Tons Carbon/ha/yr)
Douglas Fir in Washington	
Natural stands	2.8
Silvicultural treatments	
Plantation establishment	3.6
Nitrogen Fertilization	4.4
First-generation genetics	4.9
TARGET	12.5
Loblolly Pine in North Carolina Pocosins	
Natural stands	1.8
Silvicultural treatments	
Drain and plant	3.5
Bedding	4.3
Preplant phosphorus	5.3
Nitrogen fertilization	5.9
First- and second-generation genetics	7.2
TARGET	15.0
SRIC Hardwoods, Various Sites in U.S.	
Short rotation, genetics, site preparation, fertilizer, coppicing	6.5
TARGET for year 1996	10.0
Energy Crop Plantations, Temperate Zone	
Intensive management, mixed species; TARGET for year 2025	24.7
Eucalyptus Hybrids in Espirito Santo, Brazil	
Seed selection, breeding, microsite planting	18.2
TARGET	26.0

Source: Based on Farnum et al., 1983, and Marland, 1988 (Douglas fir and loblolly pine); Ranney et al., 1987 (SRIC hardwoods); Walter, 1988 (energy crop plantations); WRI et al., 1988 (Eucalyptus).

The implications for carbon fixing are clear; a 30% rise in biomass production allows 30% less land in forest -- or a 30% offtake of fuelwood or timber, either managed or poached -- to achieve the same results. Drought-resistant strains would encourage forest-sector and donor community investment in arid and degraded land projects.

The potential benefits of productivity increases on plantation forests currently are limited by the slow pace of research and field trials on promising species and varying site conditions. Eighty-seven percent of plantation forestry in the tropics focuses on species of only 3 types: pine, teak, and eucalyptus (Vietmeyer, 1986). Obstacles to expanding plantations are reviewed below.

Option 4: Improve Forest Harvesting Efficiency

Commercial forest management, especially in tropical forests with extremely high species diversity per hectare, has targeted harvesting on only about 5% of species. Reasons for this high-grading -- selective cutting of high-value trees -- include tradition, lack of demonstrated uses and educated markets for other species, and the availability of virgin stands open to resource "mining" without costly management and with government support. As a result, fully 85% of total wood produced from tropical natural forests in 1970 went unused, left as slash or wasted at the mill (Goldemberg et al., 1987).

A survey of Malaysian and Indonesian logged forests recently found that 45-75% of standing trees had been injured (Gillis, in press). In southeast Amazonia, remote sensing study has revealed that while 90,000 km^2 had been clearcut by 1985, three times that area (266,000 km^2) had been seriously damaged by logging and colonization (WRI et al., 1988; Malingreau and Tucker, 1988). Improvements in forest management would reduce waste of non-target species damaged during logging (e.g., the Celos Silvicultural System, discussed under option 1 above).

Efficient harvesting would require less virgin and mature secondary forest to be cut (Mergen and Vincent, 1987). Malaysian government policy has raised the number of commercial tree species for harvest from 100 in the mid-1960s to over 600 today (IIED and WRI, 1987). The harvest and marketing of under-used species and size classes throughout the tropics, encouraged by government regulations and forestry company practices, could reduce tree losses from harvest and improve stand yields more than silvicultural innovations could, especially in secondary forests (OTA, 1984).

Option 5: Expand Current Tree Planting Programs in the Temperate Zone

Forested area in temperate and boreal zones is considered roughly constant in most studies but may be declining in this decade (Houghton, 1988a). However, temperate forests were much larger historically and could be expanded. Some European countries have increased their net forested area: France was 14% forest in 1789; today, 25% of France is forested (Brown et al., 1988a).

According to the Forest Service report for FY 1987, total U.S. tree planting by Federal and State agencies revegetated 1.2 million hectares (3 million acres) in 1987 (USFS, 1987). Table 7-19 lists the five major tree-planting programs in the U.S. since 1935 and the number of acres planted in their highest 5-year period.

If current programs planted 1.2 million ha with existing financial and programmatic incentives geared to replacement levels of planting, then additional enticements, on the order of $220-345/ha ($90-140/ac), would probably stimulate tree planting on hundreds of thousands of hectares. The Conservation Reserve Program of USDA (see Option 2, below) paid an average of $219/ha (average rental payment of $125/ha ($50/acre) plus half of establishment costs at an average of $94/ha), to plant 648,000 ha of trees (1.6 x 10^6 ac) from 1986 to mid-1988. Youth groups could be mobilized to plant trees annually on Arbor Day or during weekend or summer work camps.

TABLE 7-19
Summary of Major Tree Planting Programs in the U.S.

Program	Period (Highest 5 years)	Acreage Planted ($x\ 10^6$) (acres)	(hectares)
Civilian Conservation Crops (CCC)	1935-39	1.4	0.6
Soil Bank	1957-61	2.0	0.8
USDA-Forest Service Reforestation	1979-83	1.5	0.6
Forestry Incentive Program (FIP), Agriculture Incentive (ACP)	1978-82	1.1	0.4
Conservation Reserve Program (USDA)	1986-90 projected 1986-88 actual	5.6 1.6	2.3 0.6

Sources: Conrad, 1986; USDA, Land Retirement and Water Quality Branch statistics on Conservation Reserve Program enrollment, November, 1988.

Large-scale reforestation by individuals, companies, and/or government programs has been proposed as a possibility in temperate zones (see Table 7-21). However, this would be far less cost effective (by perhaps a factor of 3-10) than in the tropics because of higher land costs and slower tree growth. Recent, more targeted proposals for tree planting in the U.S. focus on activation of croplands considered surplus during periods of diminished exports and high costs for farm support programs.

Option 6: Reforest Surplus Agricultural Lands

The Conservation Reserve Program (CRP) administered by USDA has been proposed as the quickest, most cost-effective way to stimulate tree planting at the scale necessary to partially offset CO_2 emissions. Planting tree carbon sinks may be comparatively cheaper than other current CO_2-limiting options, for example, planting short-rotation biomass energy plantations, investing in energy conservation measures, or scrubbing CO_2 from industrial emissions (Dudek, 1988a,b).

The CRP was established by the conservation title of the Food Security Act of 1985 to retire highly erodible cropland, reduce production and boost prices of surplus food commodities, and reduce Treasury outlays. Participating landowners contract to retire cropland for 10 years. They are reimbursed for 50% of the costs of planting the necessary vegetative cover, and receive an annual rental payment.

Participation in the tree-planting program was targeted at 12.5% of projected total retired acreage (16.2-18.2 million ha, or 40-45 million acres by 1990), or about 2.3 million ha (5.6 million acres). However, tree-planting enrollment totals only 0.40 million ha (of 10.5 million ha enrolled in CRP by November 1988), mostly in Southern states already producing plantations of loblolly pine in favorable soils and climate. Planting rates have been low due to low bid prices, farmers' reluctance to lose base acreage in Federal crop support programs, and inadequate support for tree planting by extension offices. Better financial incentives (i.e., higher bid prices, higher share of planting costs paid) may greatly increase tree acreage enrollment.

For example, all new CO_2 emissions from fossil-fuel electricity plants projected for 1987-96 could be offset by planting trees (see Table 7-20). Estimates of planned increases in fossil-fuel electric generating capacity for 1987-96 total 25,223 MW, producing 45.5 Tg C (equivalent to 166.7 million tons CO_2) (NAERC, 1987).

The uptake of CO_2 varies by species. Silver maple, for example, a relatively inefficient species, absorbs 5 t C/ha/yr under optimal conditions, while American sycamore absorbs as high as 7.5 t C/ha/yr (Steinbeck and Brown, 1976; Marland, 1988). Depending upon species chosen, it would take between 4.5-13 million ha of short-rotation (4-5 years) monocultural (single-species) plantations on good sites to offset the planned 25,223 MW of additional fossil-fuel electricity.

Mixed stands of numerous tree species are more desirable to prevent the ecological problems associated with monocultural stands -- increased pest populations, low species diversity, vulnerability of even-aged stands. The acreage requirements for mixed stands to offset 45.5 Tg C could rise to 13 million ha (32 million acres), or about 70% of the total enrollment target for the 10-year CRP program. Further analysis is necessary to take into account availability of productive soils, variations in actual site and mixed-stand productivity rates.

USDA's share of costs for establishing trees on CRP acres averages $94 per hectare, plus rental payments averaging $125 per ha per year for the 10 years of the current CRP. If the full costs of the planting are assumed to be $370/ha, and fertilizer costs are $62/ha, then the mid-range estimate of 9.1 million ha of trees added to the CRP would cost $3.9 billion to establish ($3.1 billion if current average USDA cost-share expenditures continued) (see Table 7-20). Rental payments by USDA or utilities, estimated to rise to about $250/ha/yr, would need to continue over the 50-year life of the electricity plants whose emissions would be offset.

TABLE 7-20
Estimates of CRP Program Acreage Necessary to Offset CO_2 Production from New Fossil Fuel-Fired Electric Plants, 1987-96, by Tree Species or Forest Type

Tree Species/Forest Type	Carbon Fixing Rate Used (t C/ha/yr)	Land Requirements for Offset (x 10^6) Hectares	Acres
Average growth US commercial forests 1977 (USFS, 1982)	0.82	55.5	137.1
Average growth US commercial forests fully stocked (USFS, 1982)	1.35	33.7	83.2
Estimate for large mixed stands of moderate-growth species	3.5	13.0	32.1
Silver maple (Ranney et al., 1987)	5.0	9.1	22.5
SRIC program average productivity by 1987 (Ranney et al., 1987)	6.5	7.0	17.3
American sycamore (Marland, 1988)	7.5	6.1	15.1
SRIC program target for 1996 (Ranney et al., 1987)	10.0	4.5	11.1
SRIC program, highest documented from exotics (Ranney et. al., 1987)	13.0	3.5	8.6
Loblolly pine, target after genetics (Farnum et al., 1983)	15.0	3.0	7.4

Notes:
1. New fossil fuel-fired electric utility plant emissions are assumed to be 166.7 million tons CO_2 total for period 1987-96 (or 45.5 Tg C) (Dudek, 1988a; NAERC, 1987). 1 metric ton CO_2 = 0.27 ton carbon.

2. 1 ton biomass = 0.50 ton carbon. 1 hectare = 2.47 acres. Units are expressed as metric (not English) tons/acre for comparison.

3. Rotations for all estimates are assumed to be 4-5 years.

4. The carbon fixation rates for silver maple and American sycamore differ from those cited in Dudek (1988a), following personal communication with Dudek.

Some lands not presently producing timber or crops might be available for afforestation. In 1976, the U.S. had 70 x 10^6 ha (173 million acres) of land currently not productive -- although used for recreation or other purposes -- with rainfall greater to 50 cm/yr that may offer suitable (although not optimal) habitat for tree planting (Fraser et al., 1976). Any additional lands required would have to be diverted to forestry from other competing land uses.

The stream of direct and indirect benefits that would accrue from afforestation, including timber harvest, reduced soil erosion and nonpoint source water pollution, and increases in recreation use and wildlife, has not been considered yet, and would tend to reduce costs attributed to climate change programs if utilities or farmers managed forested land for multiple uses. Quantification of these potential benefits is needed.

CO_2 uptake rates might be increased through biotechnology improvements to perhaps 10 t C/ha/yr within 10-15 years (Ranney et al., 1987). Higher uptake rates would reduce both offset acreage requirements and costs. If economic hardwood species like American sycamore (used in flooring and millwork) and silver maple (for furniture and box and crate production) or softwoods (for lumber) are harvested for durable products, carbon storage continues after harvest.

Option 7: Reforest Urban Areas

Urban areas, which currently contain 75% of the U.S. population, on 28 million ha, are increasing by 0.53 million ha (1.3 million ac) per year (USDA, 1982). A study of urban forests in 20 cities found that for every four trees removed, only one tree is planted, and for a third of the cities, only one in eight trees lost is replanted (Moll, 1987). The total number of trees in Chicago dropped by 43,853 between 1979 and 1986; trees planted per year declined from 24,675 in 1979 to 9,380 in 1980 (NASF/USFS, 1988; Open Lands Project, 1987).

An urban tree is about 15 times more valuable than a forest tree in terms of reducing CO_2 emissions. Trees break up urban "heat islands" by providing shade, which reduces cooling loads (air conditioning) in warm weather by reducing building's heat gain, and cuts heating loads in cool weather by slowing evaporative cooling and increasing wind shielding. Three strategically placed trees per house can cut home air conditioning energy needs by 10-50% (Akbari et al., 1988). Trees planted as windbreaks around houses and buildings also can reduce winter heating energy use by 10-50% (Robinette, 1977). Thus urban trees both sequester CO_2 and reduce consumption of fossil fuels, making strategic planting around buildings a small but efficient response option (Meier and Friesen, 1987). The American Forestry Association (AFA) recently conducted a survey of urban forest needs, and launched Project ReLeaf to plant 100 million trees in city streets, parks, and rural areas. AFA estimates savings of 40 billion kilowatt-hours of energy from these new trees (based on Akbari et al., 1988), which would provide a carbon cycle benefit equivalent to 4.9 Tg C annually. This benefit would accrue from a combination of absorption of CO_2 and reduced emissions from electricity generation (Sampson, 1988).

Option 8: Afforestation for Highway Corridors

Highway corridors offer significant opportunities for tree planting, along 6.2 million kilometers (km) (3.9 million miles) of roads in the U.S. In 1985, 11.9 million ha (29.5 million acres) of land (totalling 1.3% of the contiguous U.S.) were in use as highways, including right-of-ways and buffer strips -- 9.9 million ha in rural areas, and 2.0 million in urban areas (calculations based on average municipal right-of-way as 50 feet, reported in U.S. EPA, 1987; data from U.S. DOT, 1985). The North-Central states have 4.2 million ha (10.3 million acres) in roads, the South has 3.9 million ha, and the Northeast, 1.1 million ha, all regions with generally good site characteristics for tree planting. If, for example, an additional 10% of the 9.2 million acres of interstate, state, and local highway corridors in these regions were planted with trees, 0.9 million ha would be available -- about 10% of the roughly 9 million ha in trees necessary to offset new CO_2 emissions from power plants from 1987-96 (see above). At average costs of establishment and fertilization of $432/ha, total cost would approach $390 million. If 20% of highway corridors were planted, 1.8 million ha (4.52 million acres) would be produced, at a cost of $777 million.

Option 9: Reforest Tropical Countries

Numerous estimates have been made of tree planting desirable for economic, social, and environmental reasons unrelated to climate warming. One authority concludes that "at least 100 million hectares of tree planting worldwide appears necessary to restore and maintain the productivity of soil and water resources" (an area equivalent to the size of Egypt) (Brown et al., 1988a). Major tree-planting programs are being promoted in many parts of the world, partly in response to a 1985 international initiative, the Tropical Forestry Action Plan, jointly sponsored by the Food and Agriculture Organization (FAO), the United Nations Development Programme (UNDP), The World Bank, and the World Resources Institute (WRI) (see Chapter 9). In response to the Plan, global funding for forestry by multilateral development banks and bilateral agencies is expected to rise from $600 million in 1984 to $1 billion in 1988. In a parallel effort, China doubled tree planting to 8 million hectares by 1985, and planted 3.3 million ha of seedlings in 1986 alone (Houghton, 1988a, quoting FAO data), although the survival rates initially hovered around 30%. China has set a goal of 20% forest cover by the year 2000 (up from 12.7% forest in 1978) (Brown et al., 1988a).

Carbon benefits achieved from afforestation are not likely to be realized solely to slow global warming. Instead, social forestry projects designed to integrate provision of human needs with economic incentives and environmental stabilization -- with carbon-reduction goals piggybacked on top -- provide the most feasible approach.

Forest plantation planting in the tropics to date has focused on establishing commercial hardwoods (722,000 ha/yr) (WRI et al., 1988), and on providing fuelwood (550,000 ha/yr) (Brown et al., 1988a). The gap between fuelwood supply and demand in the rapidly expanding developing countries could reach 1 billion m^3 by the year 2000 (Marland, 1988). World Bank tallies suggest that

55 million ha of high-yielding fuelwood plantations will need to be established by 2000, to close this projected deficit -- fully 2.7 million ha/yr, or 5 times current fuelwood rates. Thus, allowing for overlap, Postel and Heise (Brown et. al., 1988a) calculate that a total of about 110 million ha of planting is necessary both to restore degraded lands and to provide fuel requirements in 2000, which would sequester approximately 0.7 Pg C/yr for the roughly 40-year life of the forest.

Several crude estimates have explored the possibility of very large reforestation efforts in tropical regions to provide a sink for fossil fuel emissions. For example, Sedjo and Solomon (in press) have proposed that the current annual atmospheric net increase in carbon (approximately 2.9 Pg C) could be sequestered for about 30 years in approximately 465 million hectares of plantation forests, at a cost possibly as low as $186 billion in the tropics or $372 billion in the temperate zone, a large but not inconceivable sum. This area would also produce as much as 4.7 billion cubic meters of industrial wood annually, three times the current annual harvest. The opportunity cost to society to offset carbon production from global annual deforestation of 11.3 x 10^6 ha in the tropics can be calculated from Sedjo and Solomon's replacement cost figures, and equals $400 per hectare -- or $4.5 billion per year, a sum the world community should be willing to pay for forest preservation in order to avoid paying carbon offset replanting costs. Myers (1988; see also Booth, 1988) has suggested that 300 x 10^6 ha of plantation eucalyptus or pine -- a landmass the size of Zaire -- absorbing about 10 t C/ha/yr could offset the 2.9 Pg C accumulating in the atmosphere annually. Dyson and Marland (1976) and Marland (1988) suggested that 700 x 10^6 ha of land -- an area about the size of Australia, or equal to the total global forest cleared since agriculture began (Matthews, 1983) -- in short-rotation American sycamore, fixing carbon at a rate of 7.5 t/ha/yr, would be required to offset total global production of 5 Pg C per year.

All of these estimates suffer from their application of some of the highest growth rates observed to vast tracts of highly differentiated site conditions. Also, global reforestation estimates thus far have focused on the potential for using forest growth to completely offset total or net global carbon emissions. New estimates are needed that consider more feasible offset goals and growth rates. More complete analyses, based on better field estimates of carbon fixation rates for a range of mixed-species stands and agrosilvicultural systems, are underway to identify available acreage (with adequate soils) for potential planting programs in specific countries -- to generate inductive assessments of the potential of this approach, rather than the deductive approaches utilized thus far. Table 7-21 gives a summary of preliminary estimates of forest acreage required to offset global CO_2 emissions.

Is there adequate idle land to seriously entertain the notion of massive tree planting? Houghton (1988b) has roughly calculated for tropical Asia and Africa availability of tropical land climatically and edaphically suitable for forest growth (i.e., climate and soils previously supported forest). Crude measures of land formerly in forest but presently degraded or in pasture, and not in use for crops or development, suggest that about 100×10^6 ha are available for reforestation in South and Southeast Asia (excluding arid lands in India and Pakistan). For tropical Africa, ratios of land once forested and land currently in "other land" categories in FAO estimates (FAO, 1987) are less reliable, but create a range of $20\text{-}150 \times 10^6$ ha available. Human-initiated fires set to create and maintain savanna for cattle grazing and other uses hypothetically could be suppressed (although difficult to manage in practice), potentially allowing another 191×10^6 ha of savanna to revert to closed forest along the northern savanna and in western Africa, providing an upper limit of 340×10^6 ha with potential for reforestation (Houghton, 1988b; FAO/UNEP, 1981).

Reforesting Degraded Lands. Restoration of lands formerly forested but degraded by anthropogenic practices -- logging, overgrazing, swidden and inappropriate agricultural methods -- could increase reforestation and carbon fixation rates. Forest fallow in swidden agriculture, often with low volumes of standing biomass, totals 1 billion ha globally, with another 1 billion in some form of degradation. Desertification (the reduction of biological productivity, primarily from human activities, usually in dry forests or rangelands) has moderately or severely affected 1.98 billion ha globally, especially in the African Sahel, Southern Africa, Southern Asia, and China and Mongolia (WRI, 1987; OTA, 1984). Sedjo and Solomon (in press) stress the low purchase price of degraded lands, while

TABLE 7-21
Estimates of Forest Acreage Required to Offset Various CO_2 Emissions Goals

Estimate	Location	Carbon Sequester Rate Assumed (t C/ha/yr)	Offset Goal	Hectares ($x10^6$)	Total Planting Cost ($\$ \times 10^9$)	Average Cost/ha ($)
Dyson and Marland (1976)	Temperate Zone	7.5	5 Pg C (total annual fossil fuel use)	700		
Marland (1988)	Tropics	9.6	5 Pg C (total annual fossil fuel use)	500		
Myers (1988)[1]	Tropics	10.0	2.9 Pg (net annual increase C)	300	120	398
Sedjo and Solomon (in press)	Tropics or Temperate	6.2	2.9 Pg (net annual increase C)	465	186 tropics 372 temperate	395 800-1400[2]
Woodwell (1987)	Tropics	5.0	1-2 Pg (net annual increase C from tropics)	200-400		
Postel and Heise (Brown et al., 1988a)	Tropics	6.8	0.7 Pg (C benefits from new fuelwood plantations and restored forests)	110		
Dudek (1988a,b)	U.S.	10-12	0.05 Pg (1987-96 new electric plant C)	3.4-4.5	1.6-1.9[3]	432[3]
EPA (this study)	U.S.	3.5-10	0.05 Pg (1987-96 new electric plant C)	4.5-13	1.9-5.6[3]	432[3]

Notes:

1. See also Booth, 1988.
2. Includes $400/ha land purchase cost.
3. Assumes no cost-sharing of establishment costs, and no annual rental payments (see text).

recognizing that low-productivity soils on degraded sites are likely to greatly increase acreage requirements for a given offset goal. Grainger (1988) concluded that 758 million ha of degraded tropical land (including 203 million ha forested in the past) could be restocked with forest.

The substitution of sustainable resource use practices and active reforestation on these lands can reduce further loss of woody biomass and increase rates of carbon fixing and fuelwood production. The price of establishing plantations on degraded grasslands in Indonesia has hovered around $400 per ha (JICA, 1986). For example, Houghton (1988b) estimates that by replacing swidden cultivation with permanent, low-input agriculture, about 365 x 10^6 ha of fallow land would be available for reforestation during the period 1990-2015. Managed reforestation of arid lands has been successful in some sites where natural mulch or commercial fertilizers were applied to seedlings, and native species well-adapted to local pest and environmental conditions were planted -- supplemented by cautious use of fast-growth or nitrogen-fixing leguminous exotic species, like *Leucaena*, *Pinus*, *Acacia*, and *Eucalyptus*, which tend to be more susceptible to pest invasions. Research and field tests on leguminous trees inoculated with *Rhizobium* fungi, which produce nitrogen-fixing nodules on legume roots, have shown that damaged tropical soils depleted of essential micorrhizal fungi can be replanted effectively and inexpensively (less than 1 cent per tree) (Janos, 1980).

Subtropical dry forests in the Western Hemisphere have been reduced by 98%. Botanist Daniel Janzen has organized an ambitious plan to restore dry forest cut for agriculture and manage habitat fragments to expand Guanacaste National Park in Costa Rica (Jansen, 1988a,b). The plan calls for establishing a local and international environmental educational and research program; suppressing human fire activities, cattle ranching, and agricultural clearing; purchasing intact remnant dry forest habitat adjacent to moist forest tracts or protected areas to provide seed sources; developing a management plan stressing species diversity and zoning for habitat use, including provision of economic opportunities. A closed-canopy dry forest with significant representation of its previous fauna is expected to evolve within 10-50 years. Expansion of this innovative approach throughout the dry tropics may be feasible, if stable land tenure and managed use can be attained.

In Nyabisindu, Rwanda, hillsides denuded by intensive swidden agriculture featuring rapid deforestation, soil erosion, and overgrazing, are being restored to productivity by strips of densely planted trees positioned across steep slopes to catch soil and create terraces for crops, and to produce fruit and fuelwood. The restoration project stocks these hedges from a tree nursery producing 5 million seedlings per year for farm fruit trees, shade trees lining roads and hilltop woodlots. A typical farm family can produce 25-50% more fuelwood than it consumes with this mixed crop-tree system (Dover and Talbot, 1987).

Obstacles to Large-Scale Reforestation in Industrialized Countries

Economic and institutional obstacles to widespread reforestation center on the high costs of site preparation, planting, forest management, and necessary financial incentives to private landowners. However, 1.2 million ha of trees were planted in 1987 without strong incentives (USFS, 1986). U.S. state foresters maintain that financial incentives on the order of $125-250/ha ($50-100/ac) would be sufficient to bolster reforestation of harvested woodland and surplus croplands in most states. With about 3 years' lead time, existing tree nurseries could accelerate production of seedlings enough to plant 3-10 times current acreage per year (NASF, 1988).

Ecological drawbacks to massive reforestation schemes include the low levels of genetic variability that characterize vast tracts of monocultural stands, and their reduced resistance to infestations by pests (e.g., gypsy moth, pine bark beetles) that can lead to widespread forest decline and mortality. Large-scale plantations may strain surface and ground water resources in areas already experiencing overdrafts of and escalating demand on aquifers (e.g., the Ogallala aquifer in the southern Great Plains, and Southeast coastal plain ground water) (Los Alamos National Laboratory, 1987).

Air pollution -- acid precipitation, ozone and other photochemical oxidants -- is already affecting the health of forests in the U.S., Europe, and China. Decline in at least seven coniferous and 4 broadleaf important species in European forests, and at least 8 important species in North American forests have been documented since 1979; 52% of West German and 36% of Swiss forests were in decline by 1986. In the Southeast U.S., natural-stand diameter growth rates for yellow and loblolly pines have declined 30-50% in the past 30 years (WRI and IIED, 1986; IIED and WRI, 1987).

Air pollution impacts may be exacerbated by the combined effect of warming and increased ultra-violet radiation due to ozone depletion. The long-term process of climate change is likely to complicate the task of actively expanding net forest area, a topic explored in Smith and Tirpak (1989). The increase of carbon dioxide (through the effect of CO_2 fertilization) may spur tree growth rates, but the net result of climate change on forest growth under changing temperature and precipitation conditions is difficult to predict. Early studies suggest that Southern bottomlands hardwood, oak, and pine forests, and Northern conifer forests are likely to advance northward in a doubled CO_2 scenario (as temperatures increase). The natural rate of forest migration -- about 100 to perhaps 400 km per 1000 years -- appears unlikely to keep up with the likely rate of forest decline (Davis and Zabinski, in press; Shands and Hoffman, 1987; Smith and Tirpak, 1989). Technical methods of speeding seed dispersal to favorable soils (e.g., seeding from aircraft) are not complex but may be costly, with potentially low seedling survival rates (WWF, no date).

Forests under the stress of climate change may have difficulty maintaining current productivity rates, let alone increased rates and expanded geographic range, as envisioned under reforestation policies. Forests migrating north in response to rising temperatures will tend to encounter poorer soils, slow natural seed dispersal methods, stresses on ecosystems, competition from other land use sectors and ecosystems also responding to climate change, and either reduced or increased precipitation and water supply conditions, depending on the region. While global boreal forests are likely to increase in total area and tree density (Shugart and Urban, no date), they probably will contain, on average, lower standing biomass volumes (and carbon fixation rates) than current boreal forests. Sedjo and Solomon (in press) estimate a net loss of 24 Pg C storage in global forests under a $2xCO_2$ scenario, largely due to declines in total biomass in boreal forests.

Climatic change therefore may affect the viability of reforestation strategies as a mitigation measure. Further research is needed.

Obstacles to Reforestation in Developing Countries

Tropical reforestation schemes face many obstacles. Pest management in monocultural plantations (e.g., rats, fungus, nematodes for *Leucaena* in the Philippines), and loss of genetic diversity that might allow adaptation to pest or viral infestations have proved major deterrents to large-scale plantation projects in the Philippines, at Jari, Brazil, and elsewhere. Other issues include rapid removal of soil nutrients by fast-growth species, reduced growth rates at altitudes as low as 450 meters and in frost belts for some species, and sheet erosion. Practical limitations of plantations include the large areas of land necessary, limited transportation infrastructure to move biomass to users, plantation security (fencing to prevent poaching of trees in northern Nigeria in 1976 cost $160-200 per ha), costs of establishment, and limited availability of skilled technicians (Villavicencio, 1983).

Pastures cut from tropical forests have been invaded by resilient monocultural grasses like *Imperata cylindrica* that must be suppressed before trees can survive. Research into recolonization of large, highly degraded pastures in the Amazon (Uhl, 1988) suggests that three factors inhibit reforestation: few seeds of forest species are being dispersed into pastures, because 85% of tree seeds are transported by animal pollinators that do not frequent pastures; most seeds dispersed to pastures are eaten by predators; and moisture and energy conditions near the ground surface in pastures are radically different from forest conditions.

Economic and population pressures in many regions make net afforestation difficult to achieve. China, for example, is experiencing rapid economic development that has led to housing construction that consumed 195 million cubic meters of wood (0.05 Pg C) from 1981-85, equivalent to the total annual growth of all China's forests (Brown et al., 1988a).

Other environmental stresses on extant forests -- including seasonal climatic variations, and the litany of stresses addressed for industrialized nations -- reduce their ability to meet current and projected demand for forest products, let alone newly supply large increases in productivity and plantation acreage. Persistent drought already plays a prominent role in the migration of environmental refugees from traditional agricultural areas such as the Sahel, forcing relocation in areas of marginal dry forest exposed to new pressures (Houghton, 1988a; Brown, 1988).

Summary of Forestry Technical Control Options

Slowing tropical deforestation, and rapidly expanding temperate and tropical reforestation, may offer two of the most cost-effective policy responses to increasing CO_2 emissions. However, only rudimentary estimates of the feasibility, costs, and consequences of large-scale reforestation have been performed. Table 7-22 summarizes these options. All calculations are preliminary estimates of planting costs only. Total costs of these measures are not estimated, and would vary greatly depending on land costs and management costs. These estimates are provided to give a general sense of the relative costs of these options. Few viable, global-scale plans to slow forest loss in the tropics have been advanced; most are policy options rather than technical fixes, and are discussed in chapters 8 and 9. Replacement of swidden agriculture with permanent low-input, sustainable agricultural systems offers particular promise.

Integrated natural resource management and social forestry projects -- designed to provide the full spectrum of forest and food products in demand; forest protection from swidden agriculture, logging, and fire; economic opportunities and reasonable rates of return; and cooperative management

TABLE 7-22
Comparison of Selected Forest Sector Control Options: Preliminary Estimates

	No. ha Required ($x10^6$)	Planting Cost/ha ($)	Total Planting Cost ($x10^6$ $)	Fixation Rate (t C/ha)	Carbon Offset Goal (Pg C/Sequestered)	Planting Cost/Pg Carbon ($x10^9$ $)
A. DOMESTIC U.S. OPTIONS						
Plant trees to offset annual CO_2 emissions US	240.0	432	104,000	5	1.2 Pg C/yr	10
Plant 100 million urban trees	0.0		100	5	0.052 Pg C/yr	0.2
Reforest 20% of highway corridors	1.8	432	778	5	0.009 Pg C/yr	10
Plant trees to offset new US electric plant CO_2 (1987-96)	9.1	432	3,930	5	0.045 Pg C/yr	10
Implement current forest economic opportunities at 4% ROR	58.3		0		0.164 Pg C/yr	0
B. INTERNATIONAL FORESTRY OPTIONS (TROPICS)						
Plant trees to offset new US electric plant CO_2 (1987-96) in LDCs	6.0	400	2,400	7.5	0.045 Pg C/yr	6
Plant trees in Guatemala to offset CO_2 emissions of 180 MW electric plant in US	0.1		14[1]		0.16 Pg C total over 40-year period	0.9

TABLE 7-22 (continued)
Comparison of Selected Forest Sector Control Options: Preliminary Estimates

	No. ha Required ($x10^6$)	Planting Cost/ha ($)	Total Planting Cost ($x10^6$ $)	Fixation Rate (t C/ha)	Carbon Offset Goal (Pg C/Sequestered)	Planting Cost/Pg Carbon ($x10^9$ $)
Substitute sustainable agriculture for all swidden agriculture	41					
Restore degraded lands and provide fuelwood for year 2000 and reduce tropical C release by 40%	110	400	44,000	7.5	0.7 Pg C/yr over 40 yrs.	6
Reforest tropical lands to offset global annual net increase in C	465	400	186,000	6.2	2.9 Pg C/yr	8
Replant tropical forest cut or burned each year	11.3/yr	400	4500/yr		1.0 Pg C/yr	4.5

1. This number is a total project cost including forest protection, plantation establishment, and agroforestry (see Table 7-4.11).

Note: All calculations made from estimates and references listed in this section; and all calculations are preliminary estimates of planting costs only, without management, harvest, rental or purchase costs included.

by local people and resource professionals -- are likely to be the most successful in addressing climate change effects and offset goals. Examples of two such projects are displayed in Table 7-23. These two projects were proposed to offset the lifetime CO_2 emissions of a 180 MW coal-fired electric plant planned by Applied Energy Services for Uncasville, Connecticut, by planting and managing forests in the tropics.

Our RCWP scenario envisions a "high reforestation" case (Houghton, 1988a,b), in which deforestation is gradually reduced to zero by 2025. This decline is projected through three major assumptions. First, 85% of shifting agriculture is replaced with sedentary cultivation, freeing 14.6 x 10^6 ha of fallow lands for reforestation each year, totalling 365 x 10^6 ha from 1990-2015. Second, 10 x 106 ha of pastures in Latin America are abandoned each year from 1990-2000, providing 100 million ha for reforestation; 5 million ha of grasslands are abandoned and reforested in Asia each year from 1990-2010, producing 100 x 10^6 ha; and 5 million ha of degraded land or savanna in Africa is reforested each year from 1990-2050, freeing another 300 million ha. Third, establishment of tree plantations (on 40-year rotations) grows linearly from about 1 x 10^6 ha in 1980 to about 5 x 10^6 ha in 2100. Over the 120-year period, 320 million ha are planted.

The total accumulation of carbon in terrestrial ecosystems from these three assumptions rises to about 80 Pg (assuming low biomass volumes per ha) to 183 Pg (using high-biomass assumptions). Peak carbon sequestering rates reach between 0.7 and 3.5 Pg/yr (low and high biomass assumptions), reversing the current emission of 0.4-2.6 Pg/yr from land use changes in the tropics.

Obstacles to slowing deforestation and to planting and maintaining reforested lands in the tropics include degraded soils, limited research on appropriate species and systems, limitations in institutional capabilities, perverse government incentives, and soaring population growth rates.

TABLE 7-23
Overview of Two Social Forestry Projects Proposed to Offset CO_2 Emissions of a 180-MW Electric Plant in Connecticut

Forest Attribute	CARE/WRI/Guatemala	WWF/Costa Rica
Total area of project	101,000 ha	122,000 ha
Protected in forest reserves	19,740 ha	72,000 ha
Logged or managed forests	38,000 ha	
Newly established woodlots (plantations)	13,140 ha	12,000 ha
Agroforestry lands	68,350 ha	
Carbon sequestered over 40-year life of plant	15.8 Tg C	21.8 Tg C
Cost estimate (cash and in-kind)	$14 million	$9.6 million

Note: Offset goal = 0.39 Tg C/yr.

Sources: WRI, 1988b, and Trexler, in press (Guatemala); WWF, 1988 (Costa Rica).

PART FIVE: AGRICULTURE

Agriculture contributes to the emission of greenhouse gases through three primary means: rice cultivation, nitrogenous fertilizer use, and enteric fermentation in domestic animals. Estimates place the annual contribution of rice cultivation and domestic animals at approximately 20 and 15%, respectively, of global methane production. The use of nitrogenous fertilizers is estimated to account for between 1 and 17% of the current global source of N_2O (See Chapter II - Greenhouse Gas Trends). Figure 7-22 illustrates the net effect of these agricultural sources on current greenhouse warming.

Both the magnitude of agricultural source emissions themselves and the potential effectiveness and costs of possible reduction measures are very uncertain. While considerable research has been done on the agricultural activities of interest, relatively little attention has been focused on agriculture-related emissions of greenhouse gases and how various changes in agricultural practices affect these emissions.

In the No Response scenarios (SCW and RCW), as shown in Figure 7-23, emissions from all three categories of agricultural practices are expected to increase over 1985 levels: Global CH_4 emissions from rice and enteric fermentation increase about 35% and 65%, respectively, by 2025; and N_2O emissions from fertilizer use are projected to increase 133% by 2025. By 2100, emissions from rice, enteric fermentation, and nitrogenous fertilizer increase by approximately 40%, 125%, and 175%, respectively.

In the Stabilizing Policy cases (SCWP, RCWP) it is assumed that growth in emissions from all three categories can be reduced somewhat, as shown in Figure 7-23: By 2100, methane emissions from rice are reduced about 20% from 1985 levels. Methane emissions from enteric fermentation

FIGURE 7-22

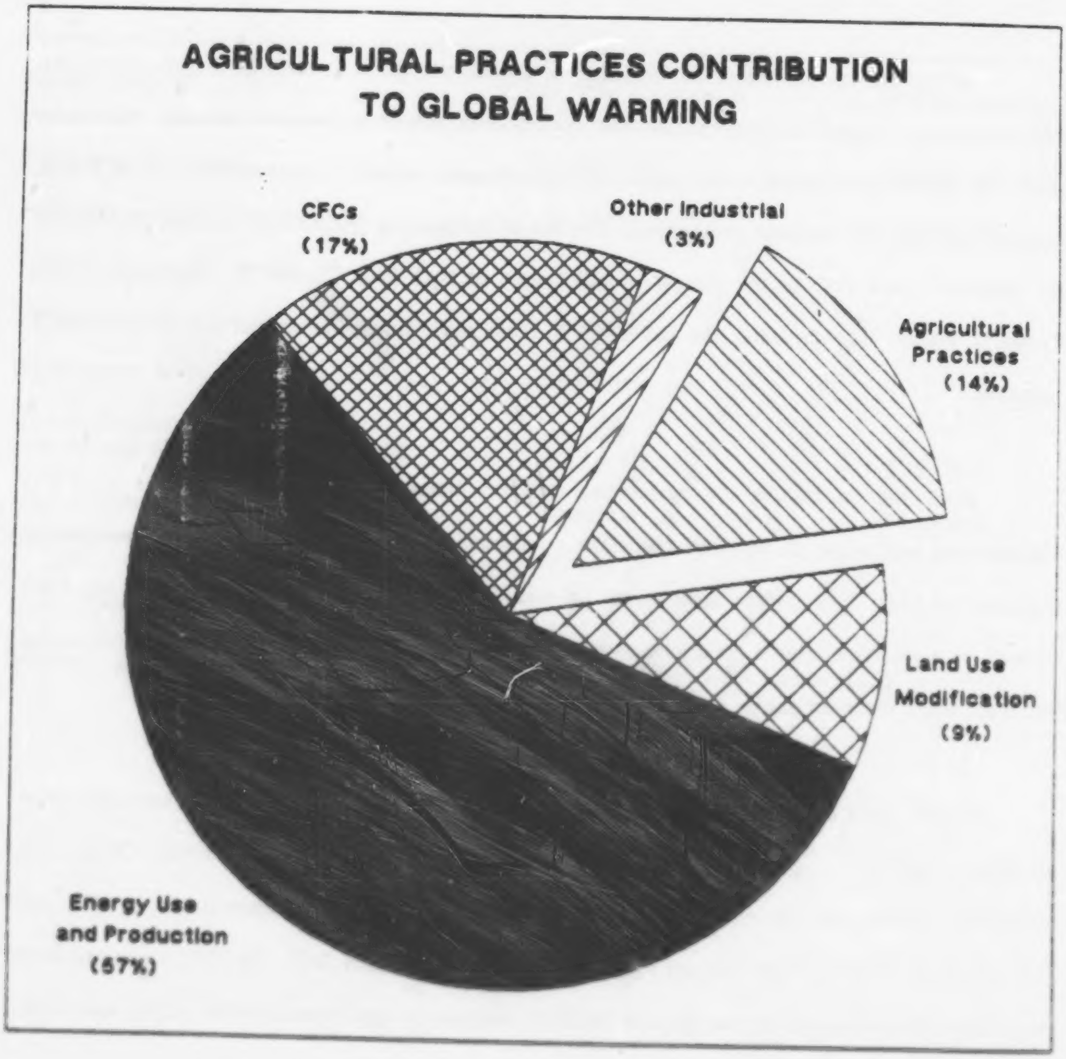
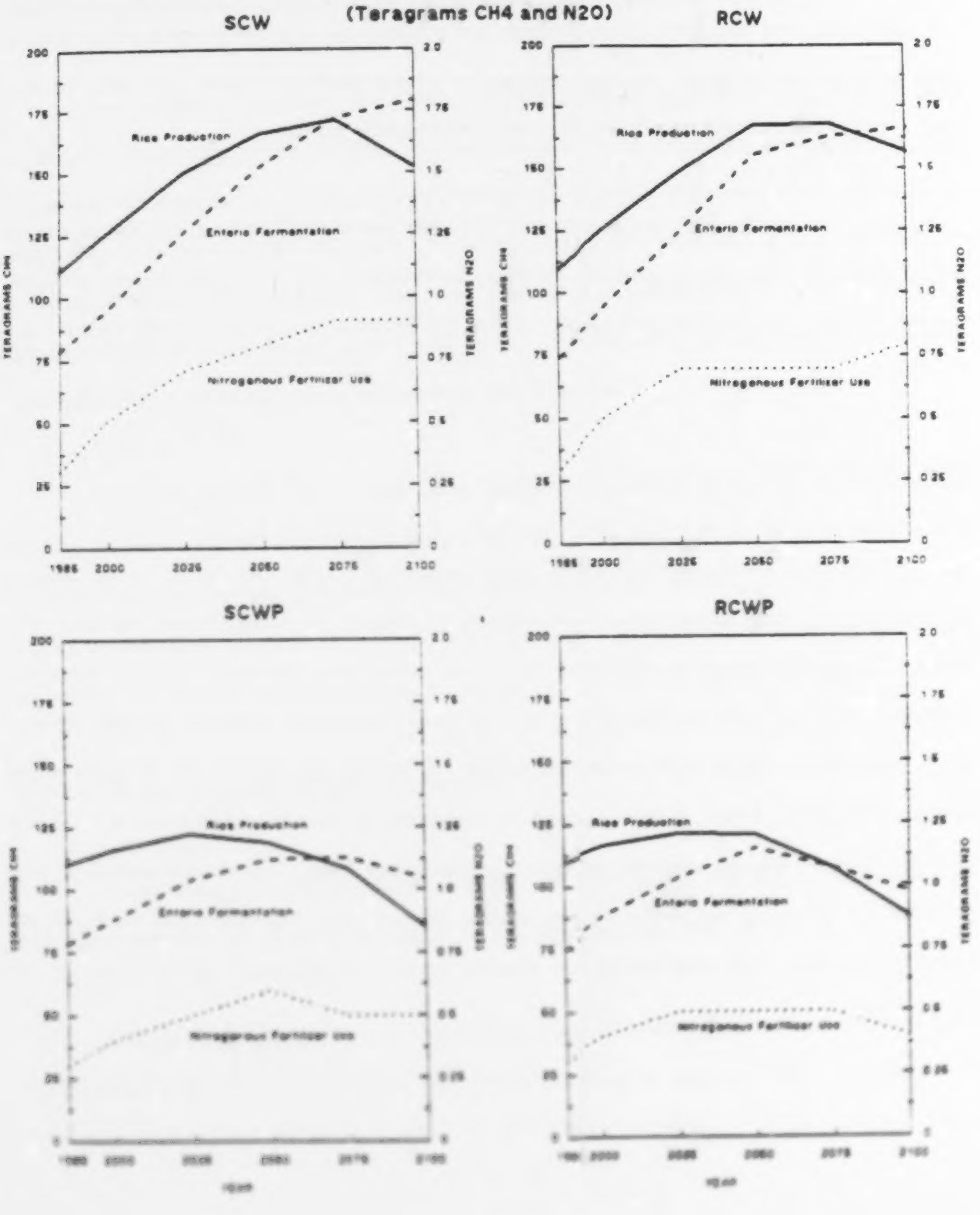

AGRICULTURAL PRACTICES CONTRIBUTION TO GLOBAL WARMING
CFCs (17%)
Other Industrial (3%)
Agricultural Practices (14%)
Land Use Modification (9%)
Energy Use and Production (57%)

FIGURE 7-23

TRACE GAS EMISSIONS FROM AGRICULTURAL ACTIVITIES

(Teragrams CH4 and N2O)



fermentation and N_2O emissions from fertilizer usage increase by 2100 in the policy cases, but at reduced rates than in the non-policy cases. Methane from enteric fermentation increases by about 32% between 1985 and 2100 in the policy cases, and N_2O from fertilizer use increases by 35-65%. It appears likely that reductions in these ranges are possible, but it is not possible at this time to precisely define the technical measures necessary to achieve these reductions, their costs, or their other (non-climate related) benefits of these emission-reducing policies.

For each of the three major trace-gas-producing agricultural practices, we discuss existing technologies and management practices, emerging technologies, and areas that require additional research. Technical options for reducing greenhouse gas emissions are discussed under each of these subsections.

RICE CULTIVATION

Methane is produced by anaerobic decomposition in flooded rice fields. Some methane reaches the atmosphere through ebullition (bubbling up through the water column), but most of it (about 95%) passes through the rice plants themselves, which act as conduits. Methane production is affected by the particular growth phase of the rice plant, temperature, irrigation practice, fertilizer usage, presence of organic matter, rice species under cultivation, and number and duration of rice harvests (Fung et al., 1988). A limited number of measurements have been performed in California, Italy, and Spain to evaluate methane production in flooded rice fields. No measurements have been published for the major rice producing areas of Asia however, where environmental conditions and cultivation practices differ significantly from those in these more temperate regions (Cicerone and Shetter, 1981).

Rice cultivation is estimated to contribute between 60 and 170 Tg methane per year currently (Fung et al., 1988), and with rice-harvested area increasing between 0.5 and 1.0% per year (IRRI, 1986), rice cultivation will continue to be a significant source of methane emissions.

Rice cultivation practices vary widely. With over 60,000 varieties of rice, there is great variation in water requirements, fertilizer response, pest and disease resistance, growing season, plant height, and yield potential. Traditional rice varieties are generally tall plants with a low grain-to-straw ratio that have a good resistance to endemic weeds and pests and a high tolerance for moisture, including flooded monsoon conditions. Cultivation of traditional varieties of rice does not involve heavy fertilization because these plants tend to lodge (fall over) at high levels of fertilization. The highest most stable rice yields are achieved with irrigation.

The research of the 1960s, which led to the Green Revolution, produced a high-yielding rice cultivar that is short, stiff-stemmed, and very fertilizer responsive. These modern, high-yielding varieties also have a short growing time, which allows for multiple plantings during the year. The first of these modern varieties, IR8, established a maximum yield potential of 10 mt/ha under ideal conditions, and reduced the growing time by a month to 130 days (Barker et al., 1985.)

Existing Technologies and Management Practices

No technology currently available can inhibit the production of methane in rice paddies, but cultivation practices and plant variety affect the amount of methane produced.

Rice Production System. The nature of the rice production system has a substantial effect on the amount of methane produced. Wet, paddy rice produces methane, while dry, upland rice does not. Wetland rice comprises about 87% of rice area worldwide. Of global rice area, about

53% is irrigated, 22.6% is shallow rainfed, 8.2% is deepwater, and 3.4% is tidal wetland. The remaining 13% is dry upland rice (Dalrymple, 1986). The majority of upland rice area is in Africa and Latin America. Rice paddies are inundated to varying depths and for different lengths of time depending on production system used, which affects the rate of CH_4 generation. How these rates differ has yet to be quantified.

Organic Matter. The kind and volume of organic matter added to the rice paddy has been shown to affect methane production. Laboratory experiments have shown that adding organic matter leads to an early peak in methane production and an overall increase equivalent to 2-5% of the added organic matter (Delwiche, 1988).

Organic fertilizers are often used in rice cultivation in Asia. Sources include animal manures, composted garbage, night soil (human feces), and plant residues. After harvest, rice plant residue is often incorporated into the soil as a source of organic material--a practice that appears to increase methane emissions. In addition, whether and to what extent the introduction of manure from domestic animals during plowing and harrowing affects methane production, are issues that must be examined.

Crop Residues. Crop residues can be burnt, buried, incorporated into the rice paddy, or used for some other activity. Burning the residue releases carbon dioxide. Buried residue partially decomposes and produces methane, but less than the amount produced by incorporating the residue into the paddy.

In southern India and Sri Lanka, there is a preference for intermediate height varieties of rice, which produce more straw for fodder and fuel (Barker et al., 1985). Finding additional uses for rice straw, such as for fiber or building materials, is necessary in order to reduce the incentive for plowing crop residue back into the field.

High-Yield Varieties. The shift to high-yield varieties of rice has helped to reduce the amount of methane produced per unit of rice. Modern, short-stemmed varieties have a grain-to-straw ratio that is about 50% higher than traditional varieties, which means less organic material (straw) is left to decompose (assuming it is not burned). In addition, the shorter growing season of high-yield varieties results in a reduction in methane emissions. However, the shorter growing season also allows multiple plantings during the course of a year. Overall methane emissions could increase as a result of multiple-planting, particularly if more organic material is incorporated into the paddies to support the greater number of plantings

High-yield varieties of rice are largely limited to irrigated areas where yield response is the highest. These modern varieties show the best fertilizer response and overall yield in irrigated areas during the dry season, when water levels are best controlled and solar energy is at its peak. The yield response is lower and highly variable under the summer monsoon conditions when flooding, pests, and diseases are most common. Some farmers in India and Bangladesh cultivate modern varieties in the dry season and traditional varieties in the wet season (Barker et al., 1985).

The uncertainty of adequate moisture in many areas, and flooded conditions in others, discourages the use of modern fertilizer-responsive varieties in non-irrigated production regimes. But, in some countries, the use of modern varieties has expanded well beyond the irrigated zones. In the Philippines, modern varieties are grown extensively in rainfed lowlands. In Burma, modern deepwater and upland varieties now cover an area three times that which is irrigated (Dalrymple, 1986; see Table 7-24).

TABLE 7-24
Water Regime and Modern Variety Adoption for Rice Production in Selected Asian Countries

		Percent rice area by water regime						
		Irrigated		Rainfed				
	Total rice area	Season			Deep Water			% Cropped in Modern
COUNTRY	(000 ha)	Dry	Wet	Shallow (b)	(c)	Floating (d)	Dryland	Varieties
Bangladesh	10190	10	2	42	26	11	9	25
Burma	4751	2	15	43	21	4	15	53
China (e)	34288	(f)	95	5	-	-	-	20 (g)
India	39515	7	32	28	12	6	15	53
Indonesia	8913	30	51	6	3	2	8	64 (g)
Korea Rep	1229	(f)	100	-	-	-	-	34
Malaysia	680	29	29	29	-	-	13	44
Nepal	1261	-	23	54	15	4	4	36 (g)
Pakistan	1999	-	100	-	-	-	-	46
Philippines	3535	17	26	34	11	-	12	85
Sri Lanka	818	27	40	27	-	-	6	89
Thailand	8679	6	14	53	12	4	11	13

Source: IRRI, 1986.

a A dash (-) indicates magnitude zero.
b 0-30 cm.
c 30-100 cm.
d More than 100 cm.
e Allocations based on impressions rather than data.
f All rice grown during the summer months and shown under wet season.
g Number of MV adoption in disagreement with "Development and Spread of High-yielding Rice Varieties in Developing Countries." AID numbers: for China - 91%; Indonesia - 82%; Nepal - 53%.

Further dissemination of the short, stiff-stemmed, fertilizer-responsive modern varieties of rice has potential for decreasing emissions of methane. World rice yield is currently at about one-half of genetic potential, which is as much as 14-16 mt/ha (Mikkelsen, 1988). There is considerable room for efficiency improvements in rice production, which would lead to a relative decrease in methane production.

Fertilizer Use. Widespread adoption of modern varieties has been somewhat impeded because of the capital required for new seed and fertilizer. Switching to modern varieties has resulted in an increase in the use of both **organic and chemical fertilizers**. Research indicates that a significant increase in production could be achieved through more efficient application of chemical fertilizer. Asia currently has a fertilizer-use efficiency of between 30 and 40%. Direct placement of fertilizer into the soil when rice is transplanted could double fertilizer-use efficiency and would increase yield (Mikkelsen, 1988).

The increase in fertilizer use and intermittent flooding of rice paddies both lead to an increase in nitrous oxide production through denitrification. (See **USE OF NITROGENOUS FERTILIZER**.)

Emerging Technologies

Current research at the International Rice Research Institute (IRRI) and other rice research centers is focused on the development of varieties better suited to a wide range of environmental conditions (Dalrymple, 1986). The development of high-yield varieties that can withstand the drought conditions of upland and shallow rainfed systems, as well as the flooded conditions associated with lowland and tidal rice cultivation, would increase the dissemination of high-yielding varieties in these areas.

Greater emphasis is being placed on efforts to understand the complexities of the farming system by conducting research in farmer's fields and encouraging farmer involvement. This so-called farming-systems style of research combines the knowledge of researchers with the direct experience of farmers (Barker et al., 1985). Research that focuses on developing cultivars that consistently produce a good yield under a wide range of conditions, rather than a high yield under ideal conditions, holds the most promise for improving food supply stability and decreasing methane emissions from rice cultivation in Asia.

There are likely to be further shifts to irrigated rice production in the future; however, improving the potential of modern varieties to perform well under rainfed conditions would reduce the incentive to shift to irrigated production systems, which are large producers of methane.

Research Needs and Economic Considerations

Before a comprehensive strategy to reduce methane production in rice can be developed, research in several areas is needed. In particular, to estimate the amount of methane produced per unit of rice we need to quantify the amount of methane produced from different cultivars, under various cultivation practices, particularly under different water management regimes. There is also a need for experiments in Asia, where the majority of the world's rice is grown and no data is currently available.

Rice is the cornerstone of the Asian economy. Many Asian countries are striving for self-sufficiency and have protected internal markets against the price fluctuations of the international market. Some countries have initiated price floors and others price ceilings. Price supports in countries such as the U.S. and Japan cause an increase in the production of rice.

USE OF NITROGENOUS FERTILIZER

Denitrification and nitrification are the primary processes that lead to the evolution of N_2O from soils fertilized with nitrogenous fertilizers. In well-aerated soils, nitrification is the primary process producing N_2O (Breitenbeck et al., 1980). Denitrification is prevalent in poorly drained, wet soils; rice cultivation is the largest agricultural contributor to denitrification losses (Hauck, 1988). Leaching of fertilizer into ground water and surface water is an additional source of nitrous oxide: between 5 and 30% of fertilizer leaves the soil system via leaching or runoff (Breitenbeck, 1988). Researchers need to derive a more precise estimate of nitrous oxide from this source.

Fertilizer-derived emissions of N_2O are estimated to be 0.14-2.4 Tg N annually (Fung et al., 1988), based on global consumption of 70.5 Tg of nitrogenous fertilizer in 1984/1985 (FAO, 1987). Nitrogenous fertilizer use is increasing at an estimated 1.3% per year in industrialized countries and 4.1% per year in developing countries (World Bank, 1988). By 2050, global fertilizer consumption is estimated to increase by a factor of 3.5 over the 1990 level (Frohberg et al., 1988).

Anthropogenic factors affecting the fertilizer-derived emissions of N_2O include the type and amount of fertilizer applied, application technique, timing of application, tillage practices, use of chemicals, irrigation practices, vegetation type, and residual nitrogen in the soil. Natural factors such as temperature, precipitation, and organic matter content and pH of soil also affect N_2O emissions (Fung, 1988).

N_2O emissions are difficult to estimate because of the complexity and variability of fertilized soil systems. Estimates suggest that fertilizer-derived emissions of N_2O are highest for anhydrous ammonia (between 1 and 5% of N applied), followed by urea (0.5% of N applied), ammonium nitrate, ammonium sulfate, and ammonium phosphate (0.1% of N applied), and nitrogen solutions

(0.05% of N applied) (Fung, 1988). Anhydrous ammonia is only used extensively in the United States, where it comprises about 38% of nitrogenous fertilizer consumption. Urea is used extensively in Asia and South America, where it accounts for 69% and 58%, respectively, of nitrogenous fertilizer consumption.

Existing Technologies and Management Practices

The wide variety of agricultural systems and fertilizer management practices produce very different quantities of N_2O emissions. These emissions can be reduced by improving the efficiency of fertilizer use, which can be achieved through changes in management, such as better placement in the soil, or in technology, for example, introducing nitrification inhibitors and fertilizer coatings, which both improve the efficiency of fertilizer applied and reduce the amount required.

Adoption of more efficient fertilizer management practices and technologies by farmers has been slow, however, particularly in developing countries. Traditional agricultural practices have proven to be difficult to dislodge. Immediate benefits of alternative practices must be made apparent or incentives provided in order to achieve widespread adoption of these more efficient practices and technologies.

Management Practices That Affect N_2O Production

Type of Fertilizer. Nitrous oxide emissions vary by one to two orders of magnitude between nitrogen solutions, urea, and anhydrous ammonia. The feasibility of using fertilizers with lower N_2O emission rates for different cropping situations needs to be examined.

best copy available

Rate and Timing of Fertilizer Application. Increased fertilizer application results in increased emissions of N_2O. Adjusting fertilizer application in accordance with plant requirements would improve fertilizer-use efficiency. Currently, fertilizer subsidies and pricing encourages a higher than optimum level of fertilizer use.

The timing of fertilizer application is likely to affect the evolution of N_2O from the soil. Limited studies on the subject suggest that emissions from fertilizer applied in the fall exceed those from fertilizer applied in the spring (Bremner et al, 1981).

Placement of Fertilizer. Proper (deep) placement of fertilizer can improve fertilizer efficiency by curbing nitrogen losses and thus N_2O emissions. Broadcasting and hand placement of fertilizer results in higher nitrogen losses than does deep placement. Deep placement is particularly important in flooded fields where fertilizer is used inefficiently. In Asia, only about one third of the nitrogen applied benefits rice crops. Placement of fertilizer into the reduced zone, which prevents microbial action, can double fertilizer-use efficiency (Stangel, 1988). This technique improves efficiency regardless of the water regime (Eriksen et al., 1985).

Rice can either be grown from seeds or transplanted. Transplanted rice may reduce denitrification losses by allowing more efficient fertilizer application. A simple tool that allows for proper fertilizer placement at the time of transplanting greatly improves fertilizer efficiency, however, this tool has not been widely adopted in Asia (Stangel, 1988). Rice farms in Asia average 3 hectares or less and are very labor-intensive operations. Consequently, there has been little incentive to develop and disseminate fertilizer technology.

Water Management. Intermittent flooding of rice paddies increases nitrogen loss and the creation of N_2O (Eriksen et al., 1985; Olmeda and Abruna, 1986).

Tillage Practices and Herbicide Use. Measurements suggest that denitrification activity and N_2O emissions are higher under no-till systems than under conventionally tilled systems (Groffman et al., 1987). This increase could be the result of fertilizer placement or the increased use of herbicides associated with no-till systems. Preliminary observations indicate that application of post-emergent herbicides leads to significant, but short-lived, increases in N_2O emissions (Breitenbeck, 1988). The influence of tillage practices and herbicide use on N_2O emissions merit further study.

Legumes as a Nitrogen Source. Few studies have been done to determine the role of nitrogen-fixing crops in the emission of N_2O. N_2O emissions from legumes have been shown to be similar to those from fertilized crop systems (Groffman et al., 1987) and to emissions from fallow unfertilized soil (Blackmer et al., 1982). Under no-till cropping systems, there seems to be a greater potential for N_2O emissions when legumes are used as the nitrogen source (Groffman et al., 1987). Although the use of legumes as a nitrogen source is unlikely to reduce emissions of N_2O from agriculture, better quantification of this source is needed.

Technologies that Improve Fertilization Efficiency

Nitrification Inhibitors. Nitrification and urease inhibitors are fertilizer additives that can increase efficiency by decreasing nitrogen loss through volatilization. Nitrification inhibitors can increase fertilizer efficiency by 30% (Stangel, 1988).

Reduced Release Rate. Techniques that limit fertilizer availability, such as slow-release or timed-release fertilizers improve nitrogen efficiency by reducing the amount of nitrogen available at any time for loss from the soil system.

Coatings. Limiting or retarding water solubility through supergranulation or by coating a fertilizer pellet with sulfur can double fertilizer efficiency (Stangel, 1988).

Emerging Technologies

No breakthrough in chemical fertilizer technology is anticipated in the near future, but there are likely to be improvements in fertilizer production and application efficiency. The development of a subsurface fertilizer application method for no-till, for example, could have a significant effect on N_2O emissions from that source.

Advances in biotechnology are likely to affect N_2O emissions from agriculture. Engineering of crop varieties that are more resistant to weeds could reduce herbicide use, and in turn, decrease the emission of N_2O.

Nitrogen-fixing cereal crops, which could be available by 2000, would decrease the use of fertilizer on those crops. The potential for reduced N_2O emissions needs to be examined (OTA, 1986).

Technological advances that increase crop yield will help reduce the amount of land and other inputs needed to produce the goods required to support the population. Improved yield and other efficiency improvements hold potential for reducing N_2O emissions.

Research Needs and Economic Considerations

Many uncertainties surround the factors influencing N_2O emissions from fertilizer. Cultivation practices and environmental practices that affect the fertilizer-derived emissions of N_2O have not been quantified. Additional research in the following areas is needed:

- N_2O emissions by fertilizer type;
- the effect of crop type on emissions;
- the effect of water management practices on emissions;
- N_2O release from drainage and ground water;
- N_2O emissions from legumes and manure;
- the effect of tillage, herbicide use, and alternative cropping systems on N_2O emissions;
- how the rate of fertilizer application affects emissions;
- the effect on emissions of different fertilizer management practices, including fertilizer placement; and
- the contribution of tropical agriculture to N_2O emissions.

Most fertilizer use in Asia is for rice cultivation. Rice is a significant source of both methane and N_2O. The production of the two gases under different management regimes needs to be explored. There is room for significant efficiency improvement in this area.

Fertilizer subsidies, target prices and loan levels encourage a higher level of fertilizer use than would otherwise occur. Such policies also reduce the attractiveness of more efficient fertilizer application and use. Increased fertilizer prices and the threat of shortages in fossil-fuel-based fertilizers should increase interest in fertilizer efficiency in the future.

ENTERIC FERMENTATION IN DOMESTIC ANIMALS

Livestock play a vital role within the agricultural sector, producing meat, dairy products and fiber. Ruminant animals, including cattle, dairy cows, buffalo, sheep, goats, and camels have the capability of converting roughages into usable nutrients through microbial fermentation. This unique capability allows them to convert cellulosic plant material to milk, meat, and fiber that would otherwise be unavailable for human consumption. Some non-ruminant animals (e.g., horses and pigs) also produce methane, although in much smaller quantities. Currently, ruminants contribute approximately 97% of the annual methane emissions from domestic animals; non-ruminants contribute approximately 3%.

Protein of animal origin has the highest biological value of all sources of protein. Within the United States, animal products supply 53% of all foods consumed, including 69% of the protein, 40% of the energy, 80% of the calcium, and 36% of the iron in our diets (English et al., 1984). In developing countries, there is a continued and growing demand for animal proteins.

About 24% of the world's land area is in permanent pasture. Rangeland and pastureland combined account for over 50% of total land area in the world. Within Africa and Oceania (Australia and New Zealand), rangeland and pastureland make up 65 and 75% of the land area, respectively (IIED and WRI, 1987). These areas are typically too steep, arid, rocky, or cold to be suitable for crops, but provide forage for about 3 billion head of cattle, buffalo, sheep and goats (FAO, 1986).

The type and function of livestock systems vary considerably around the globe. Within developed economies and countries in which meat is a major export commodity, livestock are intensively managed for either meat or dairy production. Ranches within these economies are typically large and use management techniques such as selective breeding, rangeland management, feed enhancement, and the use of antibiotics to increase cattle production.

Livestock within these systems are typically larger animals, fed at least part of the time on a high- quality grain diet. Fodder crops are grown specifically for feeding cattle. Most beef cattle are fed a high- quality, low-cellulose diet in a feedlot for several months prior to slaughter. These animals have a much higher yield of meat or dairy product than similar animals in developing countries. Table 7-25 shows average meat production per animal in several regions of the world.

Within less developed economies, livestock are usually more integrated into the whole agricultural system, frequently as a part of a crop/livestock or pasture-based system. These animals are not always managed to maximize reproductive efficiency or slaughtered at the most efficient stage of life. They are frequently maintained as scavengers and live on a low-quality forage diet.

Livestock serve as a buffer within agricultural systems by helping to stabilize cash flows and food supplies. Livestock production can serve to level out the effect of climate variability and the seasonality of rainfall in crop/livestock systems. Ruminant livestock can salvage energy and nitrogen from what otherwise could have been complete crop failures. In a grain crop failure, for example, vegetative matter suitable for livestock consumption is still produced. Livestock are convenient disposal systems for crop residues and provide a sink for surplus and damaged crops not suitable for human consumption (Raun, 1981).

In Tanzania and other Central African countries, tribal groups regard an increase in animal numbers as the best insurance against economic and social risk. The animals afford protection against the uncertainties of climate and destruction of crops by pests (Winrock, 1977). Livestock ownership enhances social status in many developing countries.

TABLE 7-25
Average Meat Yield per Animal
(kilograms)

Region	Beef & Veal	Mutton & Goat
North America	87.7	11.1
Europe & USSR	59.7	6.6
Oceania	45.8	5.7
Latin America	29.4	2.7
Near East	17.3	4.4
Far East & China	8.2	4.0
Africa	13.6	3.5
World Average	31.2	4.7

Source: Stoddart et al., 1975.

In addition to the production of meat, dairy products, and fiber, livestock are a source of fertilizer, fuel, and provide most of the tractor power in many developing countries. Animals are used for plowing, threshing, and to provide power for irrigation. Draft animals can increase farm output several times by increasing the area that a farm family can cultivate. Within Africa and the Far East, over 80% and 90%, respectively, of all draft power is provided by animals (Raun, 1981).

Animal manure is used by about 40% of the world's farmers to enhance soil fertility. Dried dung can also be used as fuel. It is estimated that over 200 million tons of manure are used each year as fuel in developing countries (Winrock, 1977).

Methane Emissions from Livestock

Enteric fermentation, the digestive process that makes livestock so useful, causes them to emit methane into the atmosphere. The 1272 million cattle, 1140 million sheep, 460 million goats, 126 million buffalo (FAO, 1985), and assorted other domesticated animals contribute an estimated 65-100 Tg of methane to the atmosphere annually. Of this amount, approximately 57% comes from beef cattle, 19% is from dairy cattle, and 9% is from sheep (Lerner et al., 1988). With the global cattle population increasing at 1.2% per year (see Chapter IV), livestock will continue to be a significant source of methane.

Livestock cannot metabolize methane. It is lost energy, which neither contributes to the animal's maintenance, nor production of a product. Estimates of gross energy intake lost as methane for cattle have ranged from 3.5% (Johnson, 1988) to 8.3% (Blaxter and Wainman, 1964).

Methane emissions from livestock are affected by differences in quantity and quality of feed, body weight, age, energy expenditure and enteric ecology. All other thing being equal, emissions are higher for animals that are heavier, have higher feeding levels and high-cellulose forage diets, and are ruminants. Emissions are also higher for work animals because some of the additional feed required to supply this energy is converted to methane (Lerner et al., 1988). Manure is an additional, unquantified source of methane (Winrock, 1977).

Although we know that animal type, feed type, and management practice affect the amount of methane generated by an animal, few modifications to current practices are certain to reduce methane production.

Existing Technologies and Management Practices

Livestock System Productivity. Intensively managed, high-productivity livestock systems--those with fewer, larger, more productive animals, produce more animal product per unit of methane (Moe and Tyrell, 1979). In these highly managed livestock systems, as the feeding level is increased, the level of methane production increases, but the energy loss in relation to gross energy intake decreases (Thorbek, 1980). An animal fed at maintenance level, however, loses a larger percentage of its gross energy intake to methanogenesis than does an animal fed at a higher level, and has no increase in animal product.

The vast differences between livestock systems in developed and developing countries make differences in productivity difficult to compare. Additional benefits, such as the work output of draft animals, must be considered, but, intensively managed, high-productivity livestock systems are the most efficient in terms of animal product yield.

Animal Type. Animal type and size affect methane production. Sheep produce less methane per animal than cattle over a shorter time period. Overall, sheep produce about 20% less methane per unit of animal product than do cattle.[1]

Diet. At low levels of feed intake, at or slightly above maintenance, a high-cellulose forage diet results in lower methane production per unit of feed than a high-nitrogen grain diet. Conversely, at high levels of feed intake, approaching three times maintenance, a high-quality grain diet results in lower methane production per unit of feed (Blaxter and Clapperton, 1965).

This information suggests that current feeding practices are reasonably good with regard to minimizing methane generation. In developing countries, where livestock are living near maintenance levels, they subsist on a high-cellulose forage diet. In developed countries, where animals consume several times the maintenance level, animals are fed a high-quality grain diet. The analysis of Blaxter and Clapperton (1965) suggests that this situation is optimal. But, further research is needed in this area, as no measurements of methane generation have been done on livestock within farm conditions of developing countries.

Feed Additives. Feed additives, which increase feed use efficiency and reduce methane generation by modifying rumen fermentation, are currently available for beef cattle. These feed additives, known as ionophores, are fed to most feedlot cattle to improve the efficiency of beef production during finishing for market. Ionophores reduce the amount of methane produced by a ruminant by improving digestive efficiency (less is produced) and by causing the animal to eat less, which leaves less food in the gut to ferment. Ionophores improve the efficiency of beef production by 6-8%, while reducing methane production by approximately 5%, for animals on a forage diet, and by approximately 20%, for animals fed a high-grain diet (Johnson, 1988).

---

[1] This estimate assumed methane production rates of 132 and 17 l/d (adapted from Johnson, 1988); weight gains of 1.05 and .22 kg/d (English et al., 1984); slaughter weights of 310 and 42 kg; and dressing percentages of .6 and .5 for cattle and sheep, respectively.

Ionophores have been shown to lose effectiveness over time, when the bacteria in the gut develops a tolerance to them (Johnson, 1974). A feeding program that alternates different ionophores can improve overall efficiency by impeding bacterial adaptation (Hubbert et al., 1987).

The use of ionophores is predominately limited to feedlot cattle because of the difficulties associated with administering a drug to range cattle. Range cattle can be fed ionophores using a mineral block lick, but few range cattle receive this drug.

Feed additives are not currently available for dairy cattle, and are unlikely to become available because of problems with efficiency and chemical residues in the milk. In developing countries, where cattle are generally used for milk and meat production, ionophores cannot be used

Methane from Manure. Microbial decomposition in manure generates methane under anaerobic conditions, but the amount produced from this source is not well quantified. Disposing of manure in lagoons and flooded fields creates anaerobic conditions conducive to the generation of methane.

Energy from manure can be captured in the form of methane in biogas plants. Manure produced by ruminants, particularly cattle and buffalo, is an ideal substrate for anaerobic fermentation in biogas plants. Methane from manure has a value of 5 kcal per cubic meter (about 70% of the energy value of natural gas). In the U.S., the dung from about 40 cows could provide all of the non-mobile fuel for a farm family, including electricity. Disposal of manure in biogas plants can reduce methane generation, while still providing a fertilizer source from the residue (Winrock, 1977).

Emerging Technologies

Efficiency improvements and advances in biotechnology have resulted in considerable productivity increases for beef cattle, dairy cattle, and sheep. Since 1940, dairy production in the U.S. has remained relatively constant while the herd size has been cut in half (English et al., 1984). Efficiency improvements should continue to produce gains in productivity, along with associated reductions in methane emissions.

Bovine growth hormone, a bio-engineered imitation of a naturally occurring protein in cattle, is expected to increase productivity in dairy cattle. This drug, which has not yet been approved by the U.S. Food and Drug Administration, is likely to decrease methane production per unit of milk (Tyrell, 1988).

The development of a methanogenesis inhibitor for dairy cattle is unlikely in the near future. Improving the ionophore delivery system for range cattle could increase use of that additive.

There is also some potential for reducing methane production by inhibiting fungus in the rumen of cattle. These fungal interactions need to be more thoroughly investigated before fungal inhibitors can be developed.

Through longer-term research in biotechnology, there exists the potential to develop microbial species capable of converting hydrogen to a useful hydrogen sink, rather than to methane. Acetic acid is such a hydrogen sink, which is useful as an energy source in cattle.

Animal scientists have long been working on the problems of improving feed-use efficiency and livestock system productivity and, thereby, the problem of methane generation. This research should continue to reduce methane generation per unit of animal product within highly managed systems.

Research Needs and Economic Considerations

Further research is needed on livestock in developing countries in order to devise a strategy to reduce methane generation. For example, estimates of methane generation are needed for a range of livestock (including draft animals) on a variety of diets. Also, the potential for using antibiotics, such as ionophores, on cattle needs to be explored.

We also need to quantify methane generation from manure under a range of management and disposal options.

Commodity programs in the U.S. encourage a larger cattle population than there otherwise would be. Unnaturally low grain prices, which are a result of deficiency payments, are, in effect, a subsidy to beef and dairy production. Beef producers are also protected by a tariff, which in recent years has been converted to a variable levy (Schuh, 1988). These policies result in a larger cattle herd and increased production of methane.

REFERENCES

PART ONE: ENERGY SERVICES

Akbari, H., J. Huang, P. Martien, L. Rainer, A. Rosenfeld, and H. Taha. 1988. The impact of summer heat islands on cooling energy consumption and global CO_2 concentration. In American Council for an Energy Efficient Economy. *Proceedings of the 1988 ACEEE. Summer Study on Energy Efficiency in Buildings*. August.

Alliance to Save Energy. 1987. *The GPU Project: Findings and Implications*. Washington, D.C.

Automotive News. 1983. Cat's 3306B Makes it Big in the Real World. November 7.

Automotive News. 1986. Chrysler Genesis Project Studies Composite Vehicles. May 5, p. 36.

Automotive News. 1988. Ford Develops Catalyst With No Platinum. December 19.

Berg, C. 1988. Industrial Processess in the Long Run. in S. Mevers. ed. *Summary of Presentations at a Workshop on Energy Efficiency and Structural Change: Implications for the Greenhouse Problem*. Oakland, CA. May 1-3, Lawrence Berkeley Laboratory, Berkeley, CA.

Bleviss, D. 1988. *The New Oil Crisis and Fuel Economy Technologies: Preparing the Light Transportation Industry for the 1990's*. Quorum Press, New York, N.Y.

Brody, H. 1987. Energy-Wise Buildings. *High Technology*. February.

Chandler, W.U. 1986. *The Changing Role of the Market in National Economies*. Worldwatch Institute, Washington, D.C. September.

Crandall, R.W., H.K. Gruenspecht, T.E. Keeler, and L.B. Lave. 1986. *Regulating the Automobile*. The Brookings Institution, Washington, D.C.

Deluchi, M.A., R.A. Johnston, and D. Sperling. 1987. *Transportation Fuels and the Greenhouse Effect*. University Wide Energy Research Group, University of California, Berkeley, CA. December.

Deringer, J.J., J.F. Busch, J. Hall, K.S. Kannon, M.D. Levine, A.C. Ayub, and I. Turiel. 1987. *Energy and Economic Analysis in Support of Energy Conservation Standards for New Commercial Buildings in Malaysia*. Lawrence Berkeley Laboratory, Berkeley, CA. April.

Edison Electric Institute. 1985. *1985 Capacity & Generation*. EEI, Washington, D.C.

FERC (Federal Energy Regulatory Commission). 1988. *The Qualifying Facilities Report*. FERC, Washington, D.C. January.

Flavin, C., and A. Durning. 1988. Raising fuel efficiency. In *State of the World 1988: A Worldwatch Institute Report on Progress Toward a Sustainable Society*. W.W. Norton and Co., New York, N.Y.

(FAO) Food and Agriculture Organization. 1981. *Agriculture: Toward 2000*. FAO, Rome.

Forster, H.J. 1983. Big Car, Too, Can be Light on Fuel. *Resources and Conservation* 10:85-102.

Geller, H.S. 1984. *The Potential for Electricity Conservation in Brazil*. Companhia Energeticer de Sao Poalo, Sao Poalo, Brazil.

Geller, H.S. 1986. *End-Use Electricity Conservation: Options for Developing Countries*. Energy Department Paper No: 32. World Bank, Washington, D.C.

Geller, H.S., M.R. Ledbetter, E.L. Miller, and P.M. Miller. 1987. *Acid Rain and Electricity Conservation*. The Energy Conservation Coalition and the American Council for an Energy Efficient Economy, Washington, D.C.

Geller, H.S. 1988. *Residential Equipment Efficiency: 1988 Update*. American Council for an Energy Efficient Economy, Washington. D.C.

Glebov, I.A. and V.P. Kovalenko. 1987. Strategies for Conservation of Fuel and Energy Resources in the Leningrad Region. *Energy* 12:(10/11)949-952.

Goldemberg, J., T.B. Johansson, A.K.N. Reddy, and R.H. Williams. 1988. *Energy for a Sustainable World*. Wiley Eastern Limited, New Dehli, India.

Goldemberg, J., T.B. Johansson, A.K.N. Reddy, and R.H. Williams. 1987. *Energy for a Sustainable World*. World Resources Institute, Washington, D.C.

Goldman, C. 1984. Measured energy savings from residential retrofits: updated results from the BECA-A projects. In American Council for an Energy Efficient Economy (ACEEE). *Proceedings of the 1984 ACEEE Summer Study on Energy Efficientcy in Buildings, Vol B.*. ACEEE, Washington, D.C.

Goldstein, D.B., and P. Miller. 1986. Developing cost curves for conserved energy in new refrigerators and freezers. In American Council for an Energy Efficient Economy. *Proceedings of the 1986 Summer Study on Energy Efficiency in Buildings, Vol. 1*. ACEEE, Washington, D.C.

Gray, C. 1983. U.S. light vehicles - some exciting news for the 1990's. *Resources and Conservation* 10:65-84.

Hewett, E.A. 1984. *Energy, Economics and Foreign Policy in the Soviet Union*. The Brookings Institution, Washington, D.C.

Hirst, E., J. Clinton, H. Geller, and W. Kroner. 1986. *Energy Efficiency in Buildings: Progress and Promise*. American Council for an Energy Efficient Economy, Washington, D.C.

Holcomb, M.C., S.D. Floyd, and S.L. Cagle. 1987. *Transportation Energy Data Book: Edition 9*. Oak Ridge National Laboratory Report No: ORNL-6325, Oak Ridge, TN.

Husselbee, W.L. 1984. *Automotive Emission Control*. Reston Publishing Co., Reston, Virginia.

IEA (International Energy Agency). 1987. *Energy Conservation in IEA Countries*. Organization for Economic Cooperation and Development, Paris.

IEA (International Energy Agency). 1988. *Energy in Non-OECD Countries: Selected Topics 1988*. Organization for Economic Cooperation and Development, Paris.

Jessup, P.S. 1988. *Advanced Power Technologies: Their Potential Contribution to Stabilizing CO_2 Emissions.*

Kahane, A., and R. Squitieri. 1987. Electricity use in manufacturing. *Annual Review of Energy* 12: pg #'s?

Kamo, R. 1987. Adiabatic diesel-Engine Technology in Future Transportation. *Energy* 12:(10/11)1073-1080.

Kavanaugh, M. 1988. End-use efficiency and NOx emissions in aviation. In S. Meyers, ed. *Summary of Presentations at a Workshop on Energy Efficiency and Structural Change: Implications for the Greenhouse Problem*. Oakland CA. May 1-3, 1988. Lawrence Berkeley Laboratory, Berkeley, CA.

Lovins, A., and R. Sardinsky. 1988. *The State of the Art: Lighting*. Competitek, The Rocky Mountain Institute, Colorado.

Maglieri, D.J., and S.M. Dollyhigh. 1982. We have just begun to create efficient transport aircraft. *Astronautics and Aeronautics* (Feb.), p.20.

Makarov, A.A., A.A. Beschinsky and A.G. Vigdorchik. 1987. Basic Principles of Energy Policy in the U.S.S.R. *Energy* 12:(10/11)945-948.

Meyers, S. 1988. *Transportation in the LDC's: A Major Area of Growth in World Oil Demand*. Lawrence Berkeley Laboratory, Berkeley, CA. March.

Miller, A.S., I.M. Mintzer, and S.H. Hoagland. 1986. *Growing Power: Bioenergy for Development and Industry*. World Resources Institute, Washington, D.C. April.

Miller, P.M., H.S. Geller and A.T. de Almeida. Undated. *Improving Energy Efficiency of Electrical Equipment in Pakistan*. American Council for an Energy Efficient Economy. Washington, D.C.

Mintzer, I.M. 1988. *Projecting Future Energy Demand in Industrialized Countries: An End-use Oriented Approach*. Prepared for U.S. EPA, Washington, D.C. 40+ pp.

Mix, T.W. 1987. Advanced Seperation Techniques for Petrochemicals. *Energy* 12:(10/11).

Naill, R. 1987. Cogeneration and Small Power Production. Presentation to the Energy Policy Forum. Airlie Va. June 16.

National Acid Precipitation Assessment Program. 1987. *Interim Assessment: The Causes and Effects of Acid Deposition*. Washington, D.C.

National Energy Conservation Center. 1986. *Potential for Energy Efficiency Improvements in the Commercial and Industrial Sectors*. Publ. city?

New England Energy Policy Council. 1987. *Power to Spare: A Plan for Increasing New England's Competitiveness Through Energy Efficiency*. Energy Policy Council, Boston, MA.

OTA (Office of Technology Assessment). 1982. *Increased Automobile Fuel Efficiency*. OTA, Washington, D.C.

OECD (Organization for Economic Co-operation and Development). 1988. *Transport and the Environment*. Paris.

Plotkin, S.E. 1989. U.S. Office of Technology Assessment, Personal communication, January 13.

Price, A. and M. Ross. 1988. *Reducing Electricity Costs in Automotive Assembly, Stamping and Parts Plants*. Unpublished.

Rocky Mountain Institute. 1986. *Advanced Electricity-Saving Technologies and the South Texas Project*. Old Snowmass, CO.

Ropelowski, R.R. 1982. 757 Key to Route Flexibility. *Aviation Week and Space Technology*. August 30, p.36.

Rosenfeld, A.H. 1988. Urban trees and light-colored surfaces: inexpensive and effective strategies for reducing air conditioning energy consumption. In Meyers S., ed. *Summary of Presentations at a Workshop on Energy Efficiency and Structural Change: Implications for the Greenhouse Problem*. Oakland CA, May 1-3, 1988. Lawrence Berkely Laboratory, Berkely, CA.

Rosenfeld, A.H. and D. Hafemeister. 1985. Energy conservation in large buildings. In D. Hafemeister et al. (eds). *Energy Sources: Conservation and Renewabies*. Conference Proceedings No. 135. American Institute of Physics, New York.

Rosenfeld, A.H. and D. Hafemeister. 1988. Energy-efficient Buildings. *Scientific American* 258:(4).

Ross, M. 1985. Industrial Energy Conservation. In Hafemeister, D., H. Kelly and B. Levi. *Energy Sources: Conservation and Renewables*. American Institute of Physics, New York.

Ross, M. 1986. *Current Major Issues in Industrial Energy Use*. Prepared for the Office of Policy Integration, U.S. Department of Energy, Washington, D.C.

Ross, M. 1987. Industrial Energy Conservation and the Steel Industry of the United States. *Energy* 12:(10/11).

Ross, M. E.D. Larson and R.H. Williams. 1987. Energy Demand and Materials Flows in the Economy. *Energy* 12:(10/11).

Sathaye, J.A., B. Atkinson and S. Meyers. 1988. *Alternative Fuels Assessment: The International Experience*. Lawrence Berkeley Laboratory, Berkeley, CA. March.

Sathaye, J.A., A.N. Ketoff, L.J. Schipper, and S.M. Lele. 1988. *An End-use Approach to Development of Long-term Energy Demand Scenarios for Developing Countries*. Lawrence Berkeley Laboratory, Berkeley, CA. September Draft.

Schipper, L., S. Meyers, and H. Kelly. 1985. *Coming in from the Cold: Energy-Wise Housing in Sweden*. Seven Locks Press, Washington, D.C.

Schipper, L., et al. 1989. Energy Use and Lifestyle: A Matter of Time? *Annual Review of Energy*. Annual Reviews Inc., Palo Alto, CA.

Smith, B.A. 1988. Douglas Initiates Marketing Efforts to Promote MD-90 Propfan Program. *Aviation Week and Space Technology*. January 25.

Smith, J.B. 1981. *Trends in Energy Use and Fuel Efficiencies in the U.S. Commercial Airline Industry*. U.S. Department of Energy, Washington, D.C.

SERI (Solar Energy Research Institute). 1981. *A New Prosperity: Building a Sustainable Energy Future. The SERI Solar/Conservation Study*. Brickhouse, Andover, MA.

Sobey, A.J. 1988. Energy use in transportation: 2000 and beyond. In Meyers S., ed. *Summary of Presentations at a Workshop on Energy Efficiency and Structural Change: Implications for the Greenhouse Problem*. Oakland CA, May 1-3, 1988. Lawrence Berkeley Laboratory, Berkeley, CA.

Stauffer, R.F. 1988. *Energy Savings from Recycling*. National Appropriation Technology Assistance Service Paper.

Turiel, I., R. Curtis and M.D. Levine. 1984. Parametric Energy Analysis in Support of Singapore Energy Conservation Standards for Commercial Buildings. K. H. Olson and W.W. Ching eds. Proceedings of the Asean Conference on Energy Conservation in Buildings. Singapore.

U.S. AID (Agency for International Development). 1988a. *New Directions for A.I.D. Renewable Energy Activities*. Office of Energy, Bureau for Science and Technology, Washington D.C. February.

U.S. AID (Agency for International Development). 1988b. *Power Shortages in Developing Countries: Magnitude, Impacts, Solution, and the Role of the Private Sector*. U.S. AID, Washington D.C. March.

U.S. DOC (Department of Commerce). 1988. *Survey of Current Business* 68(8), Bureau of Economic Analysis, Washington, D.C. August.

U.S. DOE (Department of Energy). 1987a. *Annual Review of Energy 1986*. Energy Information Administration, U.S. DOE, Washington D.C.

U.S. DOE (Department of Energy). 1987b. *Energy Security: A Report to the President of The United States*. U.S. Government Printing Office, Washington, D.C.

U.S. DOE (Department of Energy). 1987c. *Long Range Energy Projections to 2010*. Office of Policy, Planning and Analysis, U.S. DOE, Washington, D.C. September.

U.S. DOE (Department of Energy). 1988. *Annual Energy Review 1987*. Energy Information Administration Report No: DOE/EIA-0384(87), Washington, D.C.

U.S. DOT (Department of Transportation). 1988. *Federal Aviation Administration Aviation Forecasts for Fiscal years 1988 through 1999*. February.

U.S. EPA (Environmental Protection Agency). 1979.

U.S. EPA (Environmental Protection Agency). 1985. *Regulatory Impact Analysis: Oxides of Nitrogen Polutant-Specific Study and Analysis of Comments*. Office of Mobile Sources.

von Hippel, F., and B. V. Levi. 1983. Automotive Fuel Efficiency: the Opportunity and Weakness of Existing Market Incentives. *Resources and Conservation* 10:103-124.

White, L.J. 1982. *The Regulation of Air Pollutant Emissions from Motor Vehicles*. American Enterprise Institute for Public Policy Research. Washington, D.C.

Williams. 1988.

Williams, R.H., E.D. Larson, and M. Ross. 1987. Materials, Affluence, and Industrial Energy Use. *Annual Review of Energy* 12:99-144.

Wohlgemuth, J. 1988. Photovoltaic technology. In *Workshop on Global Climate Change: Emerging Energy Technologies for Electric Utilities*. Alliance Technolgies Inc., Bedford, MA. September.

The World Bank. 1985. China: The Transport Sector, Annex 6 to *China: Long-Term Development Issues and Options*. Publisher, Publisher's City.

WRI and IIED (World Resources Institute and International Institute for Environment and Development). 1988. *World Resources 1988-89*. Basic Books, Inc. New York.

PART TWO: ENERGY SUPPLY

Baldwin, S.F. (1987). Biomass Stoves: Engineering Design, Development and Dissemination. V.I.T.A., Arlington, VA.

Baldwin, S.F., H. Geller, G. Dutt, and N.H. Ravindranath. 1985. Improved Woodburning Stoves: Signs of Success. Ambio 14(4-5):280-7.

Bormann F.H., B.T. Bormann, and K.R. Smith. 1988. Earth to Hearth: A microcomputer for comparing biofuel systems. Submitted for publication.

Brown L.R. 1980. Food or Fuel: New competition for world's cropland. Worldwatch Paper 35, Washington, D.C.

Clarke, J. F. The U.S. Magnetic Fusion Energy Program. Presented at the Workshop on Global Climate Change: Emerging Energy Technologies for Electric Utilities. September, 1988.

DeMocker, J.M., J.M. Greenwald, and P.F. Schwengels. 1986. Extended Lifetimes for Coal-Fired Power Plants: Implications for Air Quality Analysis and Environmental Policy. Paper No: 28.3, Air Pollution Control Association, Annual Meeting, Minneapolis, MN, June 22-27.

EPRI, *Utility Turbopower for the 1990s*. EPRI Journal, April/May 1988

Goldemberg J., T.B. Johansson, A.K.N. Reddy, and R.H. Williams. 1988. Energy for a Sustainable World. Wiley-Eastern, New Delhi.

Grohse, E. and M. Steinberg. 1987, *Economical Clean Carbon and Gaseens Fuels from Coal and other Cabonaceous Raw Materials*. Brookhaven National Laboratory, November. (BNL 40485).

Gunnerson C.G., and D.C. Stuckey. 1986. Anaerobic Digestion: Principles and Practices for Biogas Systems. Technical Paper No. 49, World Bank, Washington,D.C.

Harvey, L.D. 1988. Potential role of electric power utilities in hydrogen economy. Paper presented at Workshop on Global Climate Change: Emergency Energy Technologies for Electric Utilities. March 30-31, 1988. American Institute of Architects, Washington, D.C.

Hay, N. P. Wilkinson, and W. James. 1988. Global climate change and emerging energy technologies for electrical utilities: The role of natural gas. Paper presented at Workshop on Global Climate Change: Current Electricity Supply Alternatives. March 30-31. American Gas Association, Washington, D.C.

Hewitt, E.A. 1984. Energy Economics and Foreign Policy in the Soviet Union. The Brookings Institution, Washington, D.C.

Hu, D., I. Oliker and F. Silaghy. 1984. Power Plant Modification for Cogeneration. Fossil Plant Life Extension Workshop, Washington D.C., June 12-15, Electric Power Research Institute.

IEA (International Energy Agency). 1987b. *Renewable Sources of Energy*. Organization for Economic Cooperation and Development, Paris.

IUCN (International Union for Conservation of Nature and Natural Resources). 1980. World Conservation Strategy for Sustainable World. Gland, Switzerland.

Jessup, P.S. *Advanced Power Technologies: Their Potential Contribution to Stabilizing CO_2 Emissions*. March 1988

Kjellstrom, B. 1985. Biomass Gasifiers for energy supply to Agriculture and small industry. Ambio 14(4-5):267-74.

Larson E.D., and R.H. Williams. 1988. Biomass-fired Steam-injected Gas Turbine Cogeneration. Proc. 1988 ASME Cogen-Turbo Symposium, Montreux, Switzerland, Aug 30-Sep 1.

Larson E.D., J.M. Ogden, and R.H. Williams. 1987. Steam-injected Gas-Turbine Cogeneration for the cane sugar industry. PU/CEES Report No 217, Princeton.

Manibog, F.R. 1984. Improved Cooking Stoves in Developing Countries: Problems and Opportunities. Ann. Rev. Energy 9:199-227.

Miller A.S., I.M. Mintzer, and S.H. Hoagland. 1986. Growing Power: Bioenergy for Development and Industry. WRI Study No 5, Washington.

NAPAP (National Acid Precipitation Assessment Program). 1987. *Interim Assessment: The Causes and Effects of Acidic Deposition*. Volume IV. NAPAC, Washington D.C.

New York Times, October 25, 1988, [article on superconductors - need complete reference] page D23

OECD (Organization for Economic Cooperation and Development). 1988. Transport and the Environment. Paris.

PEI Associates, Inc. 1988. Supply-Side Conservation Techniques for Tennessee Valley Authority and American Electric Power Coal-Fired Boilers. Cincinnati, OH. Draft Report. October.

Poole, R. 1988. Solar cells turn 30. *Science*. 241:900-901.

Ramakrishna J. 1988. Doctoral Dissertation, Dep of Geography, Univ of Hawaii, Honolulu.

Reid W.V., J.N. Barnes, and B. Blackwelder. 1988. Bankrolling Success: A portfolio of sustainable development projects. Environment Policy Institute, Washington.

Sathaye J., B. Atkinson, and S. Meyers. 1988. Alternative Fuels Assessment: the international experience. LBL mimeo, March, Berkeley.

Schlabach. T.D. 1988. Prospects for high-T_0 super conductors in large-scale power utility applications. Paper presented at Workshop on Global Climate Change: Emerging Energy Techniques for Electric Utilities. March 30-31, 1988. American Institute of Architects, Washington, D.C.

Shabecoff, P. 1987. U.S. Bureau for Water Projects Shifts Focus to Conservation. *New York Times*, October 2.

Smith K.R. 1987. The Dialectics of Improved Stoves. presented at 2nd Int. Workshop on Stove Dissemination, Antigua, Guatemala.

Smith K.R. 1987b. *Biofuels, Air Pollution and Health*. Plenum Press, New York.

Smith K.R., A.L. Aggarwal, and R.H. Dave. 1983. Air Pollution and Rural Biomass Fuels in Developing Countries. *Atmos. Envir.* 17:2343-62.

Steinberg. Cheng, and Horn, Brookhaven National Laboratory, *A Systems Study for the Removal, Recovery and Disposal of Carbon Dioxide From Fossil Fuel Power Plants in the U.S.*, 1984

United Nations. 1988. *Energy Statistics Yearbook*. United Nations, New York.

U.S. AID (Agency for International Development). 1988a. *New Directions for A.I.D. Renewable Energy Activities*. Washington, D.C. February.

U.S. AID (Agency for International Development). 1988b. *Power Shortages in Developing Countries: Magnitude, Impacts, Solutions, and the Role of the Private Sector*. Washington, D.C. March.

U.S. DOE (Department of Energy). 1985a. *Federal Ocean Energy Technology Program*.

U.S. DOE (Department of Energy). 1985b. *Five Year Research Plan 1985-1990, Wind Energy Technology: Generating Power from the Wind*.

U.S. DOE (Department of Energy). 1985c. *U.S. Geothermal Technology: Equipment and Services for Worldwide Application*. U.S. DOE, Washington, D.C.

U.S. DOE (U.S. Department of Energy). 1986. *International Energy Annual 1985*. U.S. DOE, Washington, D.C.

U.S. DOE (Department of Energy). 1987a. *Energy Security, A Report to the President of the United States*.

U.S. DOE (Department of Energy). 1987c. *Five Year Research Plan 1987-1991 National Photovoltaics Program*.

U.S. DOE (Department of Energy). 1987d. *Northern Lights: The Economic and Practical Potential of Imported Power from Canada* Office of Policy, Planning and Analysis, Report No: DOE/PE-0079, Washington, D.C. December.

U.S. DOE (Department of Energy). 1987e. *America's Clean Coal Commitment*. Office of Fossil Energy Report FE/DOE-0083, Washington D.C. February.

U.S. DOE (Department of Energy). Draft 1987. *U.S. Geothermal Energy Program, Five Year Research Plan, 1988-1992.*

U.S. DOE (Department of Energy). 1988. *Electric Power Annual 1987.* Energy Information Administration Report No: DOE/EIA-0348(87), Washigton, D.C. September.

U.S. OTA (Office of Technical Assessment). 1985. *New Electric Power Technologies.* U.S. OTA, Washington, D.C. 329 pp.

Williams, R.H. 1988. Are Runaway Energy Capital Costs a Constraint on Development? Presented at Int. Sem. on the New Era in the World Economy, Sao Paulo, Aug 31-Sep 2.

Williams, R.H. 1985. Potential Roles for Bioenergy in an Energy Efficient World. *Ambio* 14(4-5): 201-9.

Williams, R.H., and E.D. Larson. 1988. Aeroderivative Turbines for Stationary Power. *Annual Review of Energy* 13:

Williams, R.H. Draft 1988. *Advanced Gas Turbines for Stationary Power.*

World Bank. 1980. *Alcohol Production from Biomass in Developing Countries.* Washington, D.C.

World Bank. 1984. *A Survey of the Future Role of Hydroelectric Power in 100 Developing Countries.* Washington, D.C.

WRI (World Resources Institutes). 1985. *Tropical Forests, A Plan for Action.* Washington, D.C.

Wuebbles D.J., and J. Edmonds. 1988. *A Primer on Greenhouse Gases.* U.S. DOE/NBB-0083, March, Washington, D.C.

PART THREE: INDUSTRY

Bingemer, H., and P. Crutzen. 1987. The production of methane from solid wastes. *Journal of Geophysical Research* 92:2189.

Emcon Associates and Gas Recovery Systems. 1981. *Landfill Gas: An Analysis of Options.* Prepared for New York State Energy Office.

Escor, Inc. 1982. *Landfill Methane Recovery Part II: Gas Characterization.* Prepared for Gas Research Institute and Argonne National Laboratory, Department of Energy.

Gordon, J.G. 1979. *Assessment of the Impact of Resource Recovery on the Environment.* U.S. Environmental Protection Agency, Washington D.C.

Hoffman, J.S., and M.J. Gibbs. 1988. *Future Concentrations of Chlorine and Bromine.* U.S. Environmental Protection Agency Report No 400/1-88-005, Washington D.C.

Jansen, G.R. 1988. The Economics of Landfill Gas Projects. Paper from Governmental Refuse Collection and Disposal Association (GRCDA) Symposium. March, 1988.

Makhijani, A., A. Makhijani, and A. Bickel. 1988. *Saving Our Skins: Technical Potential and Policies for the Elimination of Ozone-Depleting Chlorine Compounds.* Environmental Policy Institute and the Institute for Energy and Environmental Research. Washington, D.C.

Pollock, C. 1987. Realizing Recycling's Potential. In *State of the World 1987.* W.W. Norton and Company, New York, pp. 101-121.

Rotty, R.M. 1987. A look at 1983 CO_2 emissions from fossil fuels (with preliminary data for 1984). *Tellus.* 39B:203-208.

Stauffer, R.F. 1988. *Energy Savings from Recycling.* National Appropriation Technology Assistance Service Paper.

U.S. EPA (U.S. Environmental Protection Agency). 1987. *Regulatory Impact Analysis: Protection of Stratospheric Ozone.* Office of Air and Radiation, Washington, D.C.

U.S. EPA (U.S. Environmental Protection Agency). 1988a. *Air Emissions from Municipal Solid Waste Landfills - Background Information for Proposed Standards and Guidelines.* Draft EIS. Washington, D.C.

U.S. EPA (U.S. Environmental Protection Agency). 1988b. *How Industry is Reducing Dependence on Ozone-Depleting Chemicals.* Washington, D.C.

U.S. EPA (U.S. Environmental Protection Agency). 1988c. *Report to Congress: Solid Waste Disposal in the United States.* Washington D.C.

Wilkey, M.L., R.E. Zimmerman, H.R. Isaacson. 1982. *Methane from Landfills: Preliminary Assessment Workbook.* Argonne National Laboratory, Department of Energy.

Zimmerman, R.E., G.R. Lytwynyshyn, and M.L. Wilkey. 1983. *Landfill Gas Recovery: A Technology Status Report.* Argonne National Laboratory, Department of Energy.

PART FOUR: FORESTRY

Akbari, H., J. Huang, P. Martien, L. Rainier, A. Rosenfeld, and H. Taba. 1988. The impact of summer heat islands on cooling energy consumption and CO_2 emissions. Paper presented at ACEEE Summer Study on Energy Efficiency in Buildings, Asilomar, Cal., August.

Anderson, D., and R. Fishwick. 1984. *Fuelwood Consumption and Deforestation in African Countries.* World Bank, Staff Working Papers, Number 704. The World Bank, Washington, D.C. 52 pp.

Ballard, R. 1984. Fertilization of plantations. In G. Bowen, and E. Nambiar, eds. *Nutrition in Plantation Forests.* Academic Press, London.

Bellagio, 1987. Statement of the Bellagio Strategy Meeting on Tropical Forests. Paper presented at the Bellagio Strategy Meeting on Tropical Forests, Bellagio, Italy, July 1-2, 1987.

Behmel, F., and I. Neumann. 1981. An example for agro-forestry in tropical mountain areas. Presented to the Workshop on Agro-Forestry in the African Humid Tropics, Ibadan, Nigeria.

Binkley, D. 1986. *Forest Nutrition Management.* J. Wiley and Sons, New York.

Booth, W. 1988. Johnny appleseed and the greenhouse. *Science* 242:19-20.

Brody, J. 1988. Scientists eye ancient African plant as better source of pulp for paper. *New York Times* December 13, 1988.

Brown, L. 1987. *State of the World 1987*. Norton, New York. 268 pp.

Brown, L. 1988a. *State of the World 1988*. Norton, New York.

Brown, S. 1988b. The global carbon cycle: Letter in response to Detweiler and Hall, 1988. *Science* 241:1739.

Conrad. 1986. The conservation reserve: Tree-planting windfall or tilting at windmills? *American Forests* September.

Davis, M. and C. Zabinski. in press. Rates of dispersal of North American trees: Implications for response to climatic warming. Forthcoming in *Proceedings of the Conference on Consequences of the Greenhouse Effect for Biological Diversity*. Washington, D.C., October 4-6, 1988, World Wildlife Fund-U.S.

Detwiler, R., and C. Hall. 1988a. Tropical forests and the global carbon cycle. *Science* 239:42-47.

Detwiler, R., and C. Hall. 1988b. The global carbon cycle: Response to letters. *Science* 241:1738-1739.

DOT (U.S. Department of Transportation). 1985. *Highway Statistics*. Federal Highway Administration, Department of Transportation, Washington, D.C.

Dover, M., and L. Talbot. 1987. *To Feed the Earth: Agro-Ecology for Sustainable Development*. World Resources Institute, Washington, D.C.

Dudek, D. 1988a. Offsetting new CO_2 emissions. unpublished paper, Environmental Defense Fund, New York.

Dudek, D. 1988b. Testimony before the Senate Committee on Energy and Natural Resources, September 19, 1988.

Dyson, F., and G. Marland. 1979. Technical fixes for the climatic effects of CO_2. In W. Elliott and L. Machta, eds. *Workshop on the Global Effects of Carbon Dioxide from Fossil Fuels*. U.S. Department of Energy, Washington D.C., CONF-7703585, 111-118. Proceedings of workshop at Miami Beach, Florida, March 7-11, 1977, held by DOE.

Farnum, P., R. Timmis, and J. Kulp. 1983. Biotechnology of forest yield. *Science* 219:694-702.

FAO (Food and Agriculture Organization). 1978. [[cropld nded to maintain alrdy low levels food supply. see St of Wld??]

FAO (Food and Agriculture Organization). 1981. *Tropical Forest Resources Assessment Project: Forest Resources of Tropical America, Technical Report 1; Forest Resources of Tropical Asia, Technical Report 2; Forest Resources of Tropical Africa, Technical Report 3*. Food and Agriculture Organization, Rome. UN32/6.1301-78-04.

FAO (Food and Agriculture Organization). 1986a. *Forest World Outlook Projections 1985-2000*. Forestry Paper 73. Rome.

FAO (Food and Agriculture Organization). 1986b. *The Outlook for Pulp and Paper to 1995*. FAO, Rome.

FAO (Food and Agriculture Organization). 1985. *Tropical Forestry Action Plan*. FAO, Rome.

FAO/WRI/World Bank/UNEP (Food and Agriculture Organization/World Resources Institute/World Bank/United Nations Environment Programme). 1987. *Tropical Forestry Action Plan*. Rome.

Fearnside, P.M. 1985. Brazil's Amazon forest and the global carbon problem. *Interciencia* 10:179-186.

Fearnside, P.M. 1986. Spatial concentration of deforestation in the Brazilian Amazon. *Ambio* 15:74-81.

Fearnside, P.M. 1987. Causes of deforestation in the Brazilian Amazon. In R. Dickinson, ed. *The Geophysiology of Amazonia*. John Wiley and Sons, New York.

Ford, E. 1984. The dynamics of plantation growth. In G. Bowen and E. Nambiar, eds. *Nutrition in Plantation Forests*. Academic Press, London. 17-52.

Fraser, M, J. Henry, and C. Vail. 1976. Design, operation and economics of the energy plantation. *Proceedings of Symposium, Clean Fuels from Biomass, Sewage, Urban Refuse, Agricultural Waste*. Institute of Gas Technology, Chicago. 371-95.

Gillis, M. in press. Malaysia: Public policies and the tropical forest. In R. Repetto, and M. Gillis, eds. *Public Policy and the Misuse of Forest Resources*, Cambridge University Press, Cambridge, U.K.

Goldemberg, J., T. Johansson, A. Reddy, and R. Williams. 1987. *Energy for Sustainable Development*. World Resources Institute, Washington, D.C.

Goodland, R. 1988. A major new opportunity to finance the preservation of biodiversity. In Wilson, E., ed. 1988. *Biodiversity*. National Academy Press, Washington, D.C.

Gradwohl, J., and R. Greenberg. 1988. *Saving the Tropical Forests*. Smithsonian Institution/Earthscan Books, Washington, D.C.

Grainger, A. 1987. TROPFORM: A model of future tropical hardwood supplies. In *Proceedings of CINTRAFOR Symposium on Forest Sector and Trade Models*. College of Forest Resources, University of Washington, Seattle. 205-12.

Grainger, A. 1988. Estimating areas of degraded tropical lands requiring replenishment of forest cover. *International Tree Crops Journal* 5:(1-2).

Hagenstein, P. 1988. Forests over the long haul. Paper presented at Conference on Natural Resources for the 21st Century, sponsored by American Forestry Association, Washington, D.C., November 14-17.

Hartshorn, G.S., R. Simeone, and J.A. Tosi. 1987. Sustained yield management of tropical forests: A synopsis of the Palcazu development project in the Central Selva of the Peruvian Amazon. English version of paper published in Spanish in Figueroa, J., F. Wadsworth, and S. Branham, eds. *Management of the Forests of Tropical America: Prospects and Technologies*. Institute of Tropical Forestry, Rio Piedras, Puerto Rico. 235-243.

Houghton, R. 1988a. The flux of CO_2 between atmosphere and land as result of deforestation and reforestation from 1850 to 2100. Unpublished paper prepared for Environmental Protection Agency.

Houghton, R. 1988b. Tropical lands available for reforestation. Unpublished paper and personal correspondence, submitted to Environmental Protection Agency.

Houghton, R., R. Boone, J. Melillo, C. Palm, G. Woodwell, N. Myers, B. Moore, and D. Skole. 1985. Net flux of carbon dioxide from tropical forests in 1980. *Nature* 316:(6029)617-20.

Houghton, R., R. Boone, J. Fruci, J. Hobbie, J. Melillo, C. Palm, B. Peterson, G. Shaver, G. Woodwell, B. Moore, D. Skole, and N. Myers. 1987. The flux of carbon from terrestrial ecosystems to the atmosphere in 1980 due to changes in land use: Geographic distribution of the global flux. *Tellus* 39B:122-39.

Houghton, R. 1988. The global carbon cycle: Letters in response to Detwiler and Hall, 1988. *Science* 241:1736.

IIED and WRI (International Institute for Environment and Development and World Resources Institute) 1987. *World Resources Report 1987*. International Institute for Environment and Development and World Resources Institute, Washington, D.C.

Janos, D. 1980. Mycorrhizae influence tropical succession. *Biotropica* 12 (supplement).

Jansen, D. 1988a. Tropical ecological and biocultural restoration. *Science* 239, January 15.

Jansen, D. 1988b. Tropical dry forests. In Wilson, E.O., ed. 1988. *Biodiversity*. National Academy Press, Washington, D.C.

JICA (Japan International Cooperative Agency). 1986. Technical guidance for afforestation on the grassland in Benmekat South Sumatra. ATA-186, April.

Kalpavriksh. 1985. The Narmada Valley Project--development or destruction? *The Ecologist* 15:(5-6).

Keay, R. 1978. Temperate and tropical: Some comparisons and contrasts. In J. Hawkes, ed. *Conservation and Agriculture*. Allanheld, Osmun and Co., Montclair, N.J. 243-48.

Kuusela. 1987. World Wood Supply. Ambio

Kuusela, K. 1987. Forest products -- world situation. *Ambio* 16:80-85.

Lanly, J. 1982. *Tropical Forest Resources*. FAO Forestry Paper No. 30. U.N. Food and Agriculture Organization, Rome.

Lashof, D. 1988. Technical background on reforestation as a CO_2 sink. Unpublished memorandum from Environmental Protection Agency to World Resources Institute, Washington, D.C., August 5.

Los Alamos National Laboratory. 1987. Reforestation is draining the water supply. *Los Alamos National Laboratory Newsletter* 7:31, August 14.

Lugo, A. 1988. Estimating reductions in the diversity of tropical forest species. In Wilson, E., ed. 1988. *Biodiversity*. National Academy Press, Washington, D.C.

Lundgren, and van Gelder. 1984. Agroforestry paper

Nations, J., and D. Komer. 1983. Central America's tropical rainforests: Positive steps for survival. *Ambio* 12:(5).

OECD (Organization for Economic Co-Operation and Development). 1987. *Energy Statistics, 1970-1985.* Volume 1. OECD, Paris.

OTA (Office of Technology Assessment, U.S. Congress). 1984. *Technologies to Sustain Tropical Forest Resources*. OTA-F-214, Washington, D.C., Government Printing Office.

Open Lands Project. 1987. Untitled article on urban forest replanting. *Open Lands Newsletter* XI:(2).

Palmberg, C. 1981 A vital fuelwood gene pool is in danger. *Unasylva* 33. (133)

Ranney, J., L. Wright, and P. Layton. 1987. Hardwood energy crops: The technology of intensive culture. *Journal of Forestry* September:17-28.

Repetto, R. 1988. *The Forest for the Trees? Government Policies and the Misuse of Forest Resources* (WRI, 1988)

Rich, B. 1989. The politics of tropical deforestation in Latin America: The role of the public international financial institutions. Forthcoming in S. Hecht and J. Nations, eds. *Social Dynamics of Deforestation: Processes and Alternatives*. Cornell University Press.

Robinette, G. 1977. *Landscape Planning for Energy Conservation*. Environmental Design Press, prepared by American Society of Landscape Architecture Foundation.

Ruston, J. 1988. Developing markets for recycled materials. Unpublished paper, Environmental Defense Fund, New York, 49 pp.

Sampson, R. 1988. ReLeaf for global warming. *American Forests* November/December:9-14.

Sanchez, P. 1988. Deforestation reduction initiative: An imperative for world sustainability in the twenty-first century. Paper presented at the Bureau of Science and Technology, U.S. Agency for International Development, Washington, D.C., July 22, 1988.

Sanchez, P., and J. Benites. 1987. Low-input cropping for acid soils of the humid tropics. *Science* 238:1521-1527.

Schwartzman, S. and M. Allegretti. 1987. *Extractive Reserves: A Sustainable Development Alternative for Amazonia*. Report to World Wildlife Fund-U.S.

Sedjo, R. 1988. The global carbon cycle: Letter in response to Detwiler and Hall, 1988. *Science* 241:1737.

Sedjo, R., and A. Solomon. in press. Climate and forests. Paper prepared for Workshop on Controlling and Adapting to Greenhouse Forcing, held by Environmental Protection Agency and National Academy of Sciences, Washington, D.C., June 14-15, 1988. Forthcoming in N. Rosenberg, W. Easterly, P. Crosson, and J. Darmstaedter, eds. *Greenhouse Warming: Abatement and Adaptation*. Resources for the Future, Washington, D.C.

Setzer, A., and M. Pereira. 1988. Amazon biomass burnings in 1987 and their tropospheric emissions. Unpublished manuscript, Brazilian Space Research Center, Sao Jose dos Campos, Brazil.

Maguire, A., and J. Brown, eds. 1986. *Bordering on Trouble: Resources and Politics in Latin America*. Adler and Adler, Inc., Bethesda, MD, 448 pp.

Malingreau, J-P., and C. Tucker. 1988. Large-scale deforestation in the southeastern Amazon basin of Brazil. *Ambio* 17:(1).

Marland, G. 1988. The prospect of solving the CO_2 problem through global reforestation. U.S. Department of Energy, Office of Energy Research, Washington D.C. DOE/NBB-0082, 66 pp.

Matthews, E. 1983. Global vegetation and land use: New high-resolution data base for climate studies. *Journal of Climate and Applied Meteorology* 22:474-87.

Meier, A., and J. Friesen. 1987. Strategic planting. *Energy Auditor and Retrofiter* July/August.

Mergen, F., and J. Vincent. 1987. *Natural Management of Tropical Moist Forests: Silvicultural and Management Prospects of Sustained Utilization*. Yale School of Forestry and Environmental Studies, New Haven.

McNeely, J. 1988. *Economics and Biological Diversity: Developing and Using Economic Incentives to Conserve Biological Resources*. International Union for Conservation of Nature and Natural Resources, Gland, Switzerland. 236 pp.

McNeely, J., and K. Miller. 1984. *National Parks Conservation and Development: The Role of Protected Areas in Sustaining Society*. Smithsonian Institution Press, Washington, D.C..

Miller, A., I. Mintzer, and S. Hoagland. 1986. *Growing Power: Bioenergy for Developing and Industrialized Countries*. World Resources Institute, Washington, D.C..

Moll, G. 1987. The state of our city forests. *American Forests*. May/June

Moll, G. 1988. Testimony before Senate Committee on Environment and Public Works, Washington, D.C., September.

Mwandosya, M., and M. Luhanga. 1985. Energy use patterns in Tanzania. *Ambio* 14:(4-5)237-41.

Myers, N. 1988. Tropical forests and climate. Unpublished essay dated September 28, and personal communication, Washington, D.C., October 4, 1988.

NAERC (North American Electric Reliability Council). 1987. *Electricity Supply and Demand for 1987-1996*. North American Electric Reliability Council, Princeton, NJ.

Nambiar, E. 1984. Plantation forests: Their scope and a perspective on plantation nutrition. In G. Bowen, and E. Nambiar, eds. *Nutrition in Plantation Forests*. Academic Press, London.

NASF (National Association of State Foresters). 1988. Personal communication with board of directors of NASF, annual board meeting, Washington, D.C., December.

NASF/USFS (National Association of State Foresters/U.S. Forest Service). 1988. *Forestry: A Community Tradition*. National Association of State Foresters/U.S. Forest Service, Washington, D.C., brochure.

Shands, W., and J. Hoffman. 1987. *The Greenhouse Effect, Climate change, and U.S. Forests*. The Conservation Foundation, Washington, D.C. 304 pp.

Shen, S. 1988. Biological engineering for sustainable biomass production. In Wilson, E., ed. 1988. *Biodiversity*. National Academy Press, Washington, D.C.

Shugart, H., and D.L. Urban. no date. Using Computer Models to Project Ecosystem Responses. In WWF. Proceedings of the Conference on Consequences of the Greenhouse Effect for Biological Diversity. Washington, D.C., October 4-6, 1988. in press.

Smith, J., and D. Tirpak, eds. 1989. *The Potential Effects of Global Climate Change on the United States*. Environmental Protection Agency, Report to Congress, Washington, D.C.

Steinbeck, K., and C. Brown. 1976. Yield and utilization of hardwood fiber grown on short rotations. In *Applied Polymer Symposium* no. 28, John Wiley and Sons, New York, 393-401.

Stowe, R. 1987. United States foreign policy and the conservation of natural resources: The case of tropical deforestation. *Natural Resources* 27:55-101.

Trexler, M. in press. *Social Forestry as a Response to Global Warming: A Preliminary Analysis and Case Study*.

Uhl, C. 1988. Restoration of degraded lands in the Amazon basin. In Wilson, E., ed. *Biodiversity*. National Academy Press, Washington, D.C. 326-32.

USDA (U.S. Department of Agriculture). 1982. *National Resources Inventory*. Soil Conservation Service, USDA, Washington, D.C., Statistical Bulletin 686.

U.S. EPA (U.S. Environmental Protection Agency): 1987. The transportation sector. unpublished report, Environmental Resources Inventory Project, Office of Policy Analysis, Washington D.C.

U.S. EPA (U.S. Environmental Protection Agency). 1988. The solid waste dilemma: an agenda for action. Office of Solid Waste, Washington, D.C., 70 pp. plus 3 appendices.

USFS (U.S. Forest Service, Department of Agriculture). 1982. *An Analysis of the Timber Situation in the United States, 1952-2030*. Forest Resource Report No. 23, Washington, D.C.

Vietmeyer, N. 1986. Lesser-known plants of potential use in agriculture and forestry. *Science* 232:1379-1384.

Villavicencio, V. 1983. The environmental aspects of Ipil-Ipil plantations. *Renewable Sources of Energy* 1:(1)41-65.

Wadsworth, F.H. 1983. Production of useable wood from tropical forests. In F.B. Golley, ed. *Tropical Rain Forest Ecosystems: Structure and Function*. Elsevier Scientific Publishing Company, New York. 281.

Walter, D.K. 1988. Letter to Daniel A. Lashof (U.S. Environmental Protection Agency) re: future potential worldwide bioenergy production. U.S. Department of Energy, Washington, D.C. May 26, 1988.

Winterbottom, R., et al. in press. Draft manuscript on agroforestry systems in preparation by study group on agroforestry. American Association for the Advancement of Science, David Pimentel, chair.

Winterbottom, R., and P. Hazelwood. 1987. Agroforestry and sustainable development: Making the connection. *Ambio* 16:(2-3).

Woodwell, G., R. Houghton, T. Stone, and A. Park. 1986. Changes in the area of forests in Rondonia, Amazon Basin, measured by satellite imagery. In Trabalka, J.R. and D.E. Reichle, eds. *The Changing Carbon Cycle: A Global Analysis*. Springer-Verlag. New York. 242-257.

World Bank. 1986. *The World Bank's Operational Policy on Wildlands: Their Protection and Management in Economic Development*. The World Bank, Washington, D.C. 21 pp.

Woodwell, G. 1987. The warming of the industrialized middle latitudes. Paper presented at the Workshop on Developing Policies for Responding to Future Climate Change, Villach, Austria.

Woodwell, G. 1988. The global carbon cycle: Letter in response to Detwiler and Hall, 1988. *Science* 241:1736-1737.

WRI and IIED (World Resources Institute and International Institute for Environment and Development). 1986. *World Resources Report 1986*. World Resources Institute and International Institute for Environment and Development, Washington, D.C.

WRI and IIED (World Resources Institute and International Institute for Environment and Development). 1988. *World Resources Report 1988-89*. World Resources Institute, International Institute for Environment and U.N. Environment Programme, Washington, D.C.

WRI (World Resources Institute). 1988. Power company to fund reforestation to offset carbon dioxide emissions, slow greenhouse effect. press release and press conference, October 11, Washington, D.C.

WWF (World Wildlife Fund-U.S.). 1988. The Forestry Fund: An endowment for forest protection, management, and reforestation in Costa Rica. Proposal by Conservation Foundation/World Wildlife Fund (Washington, D.C.) and Fundacion Neotropica (San Jose, Costa Rica), May 1988, 18 pp. plus 2 annexes.

WWF (World Wildlife Fund-U.S.). *Proceedings of the Conference on Consequences of the Greenhouse Effect for Biological Diversity*. Washington, D.C., October 4-6, 1988. no date.

PART FIVE: AGRICULTURE

Anderson, I., and J. Levine. 1986. Relative rates of nitric oxide and nitrous oxide production by nitrifers, dentrifers, and nitrate respirers. *Applied and Environmental Microbiology* 86:938-945.

Barker, R., R. Herdt, and B. Rose. 1985. *The Rice Economy of Asia*. Resources for the Future, Washington D.C.

Bauchop, T. 1967. Inhibition of rumen methanogenesis by methane analogues. *Journal of Bacteriology* 94:171-175.

Benz, D., and D. Johnson. 1982. The Effect of Monensin on Energy Partitions by Forage Fed Steers. Paper from Colorado State University. Fort Collins, Colorado.

Blackmer, A.M., S.G. Robbins, and J.M. Bremner. 1982. Diurnal variability in rate of emission of nitrous oxide from soils. *Soil Science Society of America Journal* 46:937-942.

Blaxter, K. and J. Czerkawski. 1966. Modifications of the methane production of the sheep by supplementation of its diet. *Journal of the Science of Food and Agriculture* 17:417-421.

Blaxter, K.L., and F.W. Wainman. 1964. Utilization of food by sheep and cattle. *Journal of Agricultural Science* 57:419.

Blaxter, K.L., and J.L. Clapperton. 1965. Prediction of the amount of methane produced by ruminants. *British Journal of Nutrition* 19:511.

Breitenbeck, G.A. 1988. Presentation at EPA's Workshop on Agriculture and Climate Change. Washington DC, February, 1988, and subsequent correspondence.

Breitenbeck, G.A., A.M. Blackmer, and J.M. Bremner. 1980. Effects of different nitrogen fertilizers on emission of nitrous oxide from soil. *Geophysical Research Letters* 7:85-88.

Breitenbeck, G.A., and J.M. Bremner. 1986a. Effects of various nitrogen fertilizers on emission of nitrous oxide from soils. *Biology and Fertility of Soils* 2:195-199.

Breitenbeck, G.A., and J.M. Bremner. 1986b. Effects of rate and depth of fertilizer application on emission of nitrous oxide from soil fertilized with anhydrous ammonia. *Biology and Fertility of Soils* 2:201-204.

Bremner, J.M., and A.M. Blackmer. 1978. Nitrous oxide: Emission from soils during nitrification of fertilizer nitrogen. *Science* 199:295-296.

Bremner, J. M., and A. M. Blackmer. 1980. *Natural and Fertilizer-Induced Emissions of Nitrous Oxide from Soils*. Air Pollution Control Association, Montreal, Quebec, p.1-13.

Bremner, J.M., G.A. Breitenbeck, and A.M. Blackmer. 1981. Effect of anhydrous ammonia fertilization on emission of nitrous oxide from the soil. *Journal of Environmental Quality* 10:77-80.

Cicerone, R.J., and J.D. Shetter. 1981. Sources of atmospheric methane: Measurements in rice paddies and a discussion. *Journal of Geophysical Research* 86:7203-7209.

Crutzen, P., I. Aselmann, and W. Seiler. 1986. Methane production by domestic animals, wild ruminants, other herbivorous fauna, and humans. *Tellus* 38B:271-284.

Dalrymple, D. 1986. *Development and Spread of High-Yielding Rice Varieties in Developing Countries*. Bureau for Science and Technology, Agency for International Development, Washington, D.C.

Delwiche C. 1988. Methane emission rates. Presented at U.S. EPA Workshop on Agriculture and Climate Change, Washington, D.C., February 29-March 1, 1988.

Eichner, M. 1988. *Current Knowledge of Fertilizer-Derived Nitrous Oxide Emissions*. Prepared for U.S. EPA, Washington, D.C.

Eliassen, K., and W. Zawadzki. 1985. Effects of monensin on polyamine formation in rumen liquid of small ruminants. *Zentralblatt for Veterinarmedizin (Journal of Veterinary Medicine)* 32:356-367.

English, B., J. Maetzold, B. Holding, and E. Heady. 1984. Future Agricultural Technology and Resource Conservation. Proceedings of the RCA Symposium: Future Agricultural Technology and Resource Conservation, Dec. 5-9, 1982, Washington, D.C. The Iowa State University Press, Ames, Iowa.

Eriksen A., M. Kjeldby, and S. Nilsen. 1985. The effect of intermittent flooding on the growth and yield of wetland rice and nitrogen-loss mechanism with surface applied and deep placed urea. *Plant and Soil* 84:387-401.

FAO (Food and Agricultural Organization of the United Nations). 1986. *1985 FAO Production Yearbook* Vol. 39. FAO, Rome.

FAO (Food and Agriculture Organization of the United Nations). 1987. *1986 FAO Fertilizer Yearbook.* Vol 36, FAO, Rome. 124 pp.

Frohberg, K., and P.R. Vande Kamp. 1988. Results of Eight Policy Scenarios for Reducing Agricultural Sources of Trace Gas Emissions. Center for Agricultural and Rural Development, Iowa State University. Report prepared for U.S. EPA, Washington, D.C.

Fuller, J., and D. Johnson. 1981. Monensin and lasalocid effects on fermentation in vitro. *Journal of Animal Science* 53:1574-1580.

Fung, I. 1988. Agriculture Emission Coefficients Estimates. Presented at U.S. EPA Workshop on Agriculture and Climate Change, Washington, DC, February 29-March 1, 1988, and subsequent correspondence.

Fung, I., E. Matthews, and J. Learner. 1988. Trace Gas Emissions Associated with Agricultural Activities. Prepared for the EPA Workshop on Agriculture and Climate Change, Washington, D.C. February 1988.

Garrett, W.H. 1982. Influence of monensin on the efficiency of energy utilization by cattle. In Ekern, A., and F. Sundstol, ed. Energy metabolism of farm animals. *European Association for Animal Production publication* 29:104.

Groffman, P., P. Hendrix, and D. Crossley. 1987. Nitrogen dynamics in conventional and no-tillage agroecosystems with inorganic fertilizer or legume nitrogen inputs. *Plant and Soil* 97:315-332.

Hauck, R. 1988. Projections of Fertilizer Use. Presented at U.S. EPA Workshop on Agriculture and Climate Change, Washington, D.C., February 29-March 1, 1988, and subsequent correspondence.

Hubbert, M., M. Branine, M.L. Galyean, G.T. Lofgreen, and D.P. Garcia. 1987. *Influence of Alternative Feeding of Monensin and Lassaload on Performance of Feedlot Heifers-Preliminary Data.* Clayton Livestock Research Center Progress Report No. 47, Clayton, New Mexico.

IIED and WRI (International Institute for Environment and Development and World Resources Institute). 1987. *World Resource Report - 1987.* Basic Books, New York.

IRRI (International Rice Research Institute). 1986. *World Rice Statistics 1985.* IRRI, Manila, Philippines.

Johnson, D.E. 1974. Adaptational responses in nitrogen and energy balance of lambs fed a methane inhibitor. *Journal of Animal Science* 38:154-157.

Johnson, D.E. 1988. Livestock Emissions Estimates. Presented at U.S. EPA Workshop on Agriculture and Climate Change, Washington, D.C., February 29-March 1, 1988, and subsequent correspondence.

Leedle, J., and R. Greening. 1988. Postprandial changes in methanogenic and acidogenic bacteria in the rumens of steers fed high- of low-forage diets once daily. *Applied and Environmental Microbiology* 54:(2) 502-506.

Lerner, J., E. Matthews, and I. Fung. 1988. Methane emission from animals: A global high-resolution database. *Global Biogeochemical Cycles* 2:139-156.

Mikkelsen, D. 1988. Technological Options for Limiting Emissions. Presented at U.S. EPA Workshop on Agriculture and Climate Change, Washington, D.C., February 29-March 1, 1988.

Moe, P. and H. Tyrell. 1979. Methane production in dairy cows. *Journal of Dairy Science* 62:1583-1586.

Olmeda, R., and F. Abruna. 1986. Four nitrogen levels and three water management systems on rice yield and nitrogen recovery. *The Journal of Agriculture of the University of Puerto Rico* 70:197-205.

OTA (Office of Technology Assessment). 1986. *Technology, Public Policy, and the Changing Structure of American Agriculture*. OTA, United States Congress, Washington, D.C.

Patrick, W. 1982. Nitrogen Transformations in Submerged Soils. *Nitrogen in Agricultural Soils*. Agronomy Monograph no. 22. Madison, Wisconsin.

Raun, N. 1981. Livestock as a buffer against climate change. In Winrock. *Food and Climate Review 1980-81*. Food and Climate Forum. Aspen, CO.

Rumpler, W., D. Johnson, and B. Bates. 1986. The effect of high dietary cation concentration on methanogenesis by steers fed diets with and without ionophores. *Journal of Animal Science*. 62:1737-1741.

Schuh, G.E. 1988. Agricultural Policies for Climate Changes Induced by Greenhouse Gases. Report prepared for U.S. EPA, Washington, D.C.

Smith, C., M. Wright, and W. Patrick. 1983. The effect of soil redox potential and pH on the reduction and production of nitrous oxide. *Journal of Environmental Quality* 12:186-188.

Stangel, P. 1988. Technological Options Affecting Emissions. Presented at U.S. EPA Workshop on Agriculture and Climate Change, Washington, DC, February 29-March 1, 1988, and subsequent telephone conversations.

Stoddart, L., A. Smith, and T. Box. 1975. *Rangeland Management*. McGraw-Hill, New York.

Thorbek, G. 1980. *Commission on Animal Nutrition, Factors Influencing Energy Losses During Metabolism. Evaluation of Energy Systems. Energy Losses in Methane*. National Institute of Animal Science, Copenhagen.

Tyrell, H. 1988. Livestock Emissions Estimates. Presented at U.S. EPA Workshop on Agriculture and Climate Change, Washington, DC, February 29-March 1, 1988.

U.S. EPA (U.S. Environmental Protection Agency). 1988. Meeting Summary of Workshop on Agriculture and Climate Change. A report prepared for EPA by J,T&A, Inc. Washington, D.C.

Wedegaertner, T., and D. Johnson. 1983. Monensin effects on digestibility, methanogenesis and heat increment of a cracked corn-silage diet fed to steers. *Journal of Animal Science* 57:168-177.

Whitelaw, F., J. Eadie, L. Bruce, and W. Shand. 1984. Methane formation in faunted and ciliate-free cattle and its relationship with rumen volatile fatty acid proportions. *British Journal of Nutrition* 52:261-275.

Winrock. 1977. *Ruminant Products: More than Meat and Milk*. Windrock International Livestock Research and Training Center. Morrilton, Arkansas.

World Bank. 1988. *World Bank, FAO, UNIDO Fertilizer Working Group Nitrogen Supply, Demand and Balances for 1986/87 to 1992/93*. Washington, D.C.

CHAPTER VIII

POLICY OPTIONS

FINDINGS VIII-2

INTRODUCTION VIII-6

INTERNALIZING THE COST OF CLIMATE CHANGE RISKS VIII-8
- **Evidence of Market Response to Economic Incentives: Energy Pricing** VIII-9
- **Financial Mechanisms to Promote Energy Efficiency** VIII-14
- **Creating Markets for Conservation** VIII-16
- **Limits to Price-Oriented Policies** VIII-18

REGULATIONS AND STANDARDS VIII-22
- **Existing Regulations that Restrict Greenhouse Gas Emissions** VIII-23
  - Regulation of Chlorofluorocarbons VIII-24
  - Energy Efficiency Standards VIII-25
  - Air Pollution Regulations VIII-28
  - Waste Management VIII-29
  - Utility Regulation VIII-31
- **Existing Regulations that Encourage Emissions Reductions** VIII-35

RESEARCH AND DEVELOPMENT VIII-39
- **Energy Research and Development** VIII-40
- **Global Forestry Research & Development** VIII-45
- **Research to Eliminate Emissions of CFCs** VIII-46

INFORMATION AND TECHNICAL ASSISTANCE PROGRAMS VIII-47

CONSERVATION EFFORTS BY FEDERAL AGENCIES VIII-50

STATE AND LOCAL EFFORTS VIII-52

PRIVATE SECTOR EFFORTS VIII-57

COMPLEMENTARY STRATEGIES TO REDUCE GREENHOUSE GAS EMISSIONS . . VIII-59

IMPLICATIONS OF POLICY CHOICES AND TIMING VIII-63

SENSITIVITY TESTS OF THE EFFECT OF ALTERNATIVE POLICIES ON GREENHOUSE GAS EMISSIONS: RISK TRADE-OFFS VIII-67
- **Policies That Increase Greenhouse Gas Emissions** VIII-69
- **Policies Designed to Reduce Greenhouse Gas Emissions** VIII-76
- **Conclusions From the Sensitivity Tests** VIII-78

REFERENCES VIII-83

FINDINGS

- If limiting U.S. and global emissions of greenhouse gases is desired, government action will be necessary. Market prices of energy from fossil fuels, products made with CFCs, forest and agricultural products and other commodities responsible for greenhouse gas emissions do not reflect the costs associated with the risk of climate change. As a result, increases in population and economic activity will cause emissions to grow in the absence of countervailing government policies to modify and/or supplement market signals.

- Policy preferences will vary among nations. However, nations can choose among many complementary policy options to reduce emissions consistent with governmental systems and other societal needs.

- There is an important distinction between short-term and long-term policy options. In the short-term, the most effective means of reducing emissions is through strategies that rely on pricing and regulation. In the long-term, policies to increase research and development of new technologies and to enhance markets through information programs, government purchases, and other means could also make a major contribution.

- The most direct means of allowing markets to incorporate the risk of climatic change is to assure that the prices of fossil fuels and other sources of greenhouse gases reflect their full social costs. It may be necessary to impose emission fees on these sources according to their relative contribution to global warming in order to accomplish this goal. This would also raise revenues that could finance other programs. The acceptability of such fees will vary among countries, but would be enhanced if equitably structured.

- Regulatory programs would be a necessary complement when pricing strategies are not effective or produce undesirable impacts. In the U.S., greenhouse gas emissions are influenced by existing federal regulatory programs to control air pollution, increase energy efficiency, and recycle solid waste. Reducing greenhouse gas emissions could be incorporated into the goals of these programs. New programs could focus directly on reducing greenhouse gas emissions through requirements such as emissions offsets (e.g., tree-planting), performance standards, or marketable permits.

- Over the long-term, other policies may be needed to reduce emissions and can complement pricing and regulatory strategies. Other policy options include redirecting research and development priorities in favor of technologies that could reduce greenhouse gas emissions, information programs to build understanding of the problems and solutions, and the selective use of government procurement to promote markets for technological alternatives.

- State and local government policies in such areas as utility regulation, building codes, waste management, transportation planning, and urban forestry could make an important contribution to reducing greenhouse gas emissions.

- Voluntary private efforts to reduce greenhouse gas emissions have already provided valuable precedents for wider action and could play a larger role in the future.

- Government policy is already exerting considerable influence on the rate of growth in greenhouse gases. Policies adopted or under consideration to promote greater use of coal, reduce required improvements in automobile efficiency, subsidize electricity consumption, and similar measures may significantly accelerate the rate of U.S. greenhouse gas emissions. A modeling exercise shows that a combination of policies that increase greenhouse gas emissions globally could substantially increase the rate of climatic change.

- Policies to create incentives to improve energy efficiency, promote renewable energy technologies, encourage tree planting, and other strategies for reducing emissions could substantially reduce emissions. A modeling exercise combining aggressive use of these policies shows that such measures could reduce the rate of warming to levels that may greatly enhance the potential for adaptation by natural and economic systems.

- Near-term actions to reduce greenhouse gas emissions will be necessary if it is decided to limit the concentration of greenhouse gases and facilitate future reductions. Atmospheric concentrations of most greenhouse gases will decline much more slowly than emissions. Delay would allow time to increase knowledge of risks and refine the choice of policies but could substantially increase the cost and reduce the effectiveness of policy responses. Time will be needed to agree on and implement policy responses since rapid changes in patterns of energy use and the industrial infrastructure responsible for emissions are likely to be disruptive and expensive.

- Most of the policies necessary to limit the buildup of greenhouse gases, such as improving energy efficiency and reversing deforestation, would produce other substantial short-term benefits. Policies to limit emissions can therefore be implemented consistent with other important economic and environmental goals.

INTRODUCTION

If the government desires to stabilize the concentration of greenhouse gases, short-term actions must be considered. Market forces do not reflect the risks of climate change and therefore, barring government intervention, emissions--and the risks of climate change--can be expected to grow. The costs of taking action may increase with time; it takes many years to develop new technologies, implement policies and replace the existing capital stock. The chemistry of the atmosphere also has long lags so that even large reductions in emissions are likely to cause atmospheric concentrations of greenhouse gases to decline very slowly or even increase. The earth would continue to warm and the climate to change for decades after atmospheric concentrations of greenhouse gases were stabilized.

Near-term government action to reduce emissions may consist entirely of policies that will contribute other substantial short-term benefits. The justification for policies that reduce greenhouse gas emissions may, therefore, be much greater than it would appear from a traditional comparison of costs and benefits. Finally, decisions not to take action to reduce emissions could also facilitate policies that result in increased emissions since such policies are presumably less likely if they contravene the purpose of other programs. This is a significant risk as we discuss later in this chapter; several recently proposed policies have the potential to significantly increase greenhouse gas emissions.

The government may pursue many policy alternatives to reduce greenhouse gas concentrations. In the short-term, economic incentives and regulatory strategies will be most effective, but in the long-run other policies will complement and support these approaches. Strategies to reduce greenhouse gas emissions can contribute to other goals, including economic growth, enhanced energy security, and a cleaner environment.

The preceding chapter shows the wide range of measures available to limit greenhouse gas emissions. Many of these measures are nearly cost-competitive or are expected to be soon. Is government intervention to reduce emissions therefore necessary? The analysis done for this report strongly suggests that without such action emissions will increase significantly. Without government intervention, there may be insufficient market incentive to develop and adopt the measures identified in Chapter VII.

In the absence of government intervention, market prices will not reflect the cost to society of activities that are detrimental to the environment. Accordingly, we will not see a reduction in consumer demand of goods and services that increase environmental risk.

The obstacles to bringing about consumer response to environmental dangers are particularly challenging for global problems like ozone depletion and the greenhouse effect. In this situation, there is the danger of what is commonly termed the "tragedy of the commons," the ecological destruction that can occur from uncontrolled use of shared resources like the atmosphere. There is probably no country for which reductions in global warming provide an adequate economic incentive to reduce greenhouse gas emissions unilaterally, even though such action could yield substantial global benefits. From any one country's viewpoint, the costs of controlling emissions may exceed the benefits since, without international agreement, reductions achieved by one nation may be offset by another. Therefore, even though the entire world may be better off as a result of efforts to lower emissions, new economic incentives are necessary to lead the market to a socially efficient outcome.

The remainder of this chapter describes the range of domestic and international policies that could be adopted to reduce emissions of greenhouse gases, and also discusses the results of modeling analyses of government actions that could reduce or increase such emissions.

There are many possible policy responses to reduce greenhouse gas emissions; none is likely to be totally effective without other supporting programs. However, as previously mentioned, consumers are not likely to reduce their demand for products and services that produce emissions of greenhouse gases unless the cost begins to exceed the benefits derived. In addition, other policies will be much less effective in the absence of economic incentives. In the short term, economic incentives and regulatory programs are likely to be the most effective policies. In the long term, research and development, information and educational activities, government procurement, and other policies can make a substantial contribution.

The policies discussed here are most applicable to the United States. However, many of the ideas reviewed are likely to be potentially suitable to other countries. Policies most suitable for developing countries are discussed in Chapter IX. However, some programs developed in the U.S., such as energy conservation programs financed by electric utilities, may have even greater relevance for developing countries, which have higher interest costs and a greater need for new generating capacity.

INTERNALIZING THE COST OF CLIMATE CHANGE RISKS

One of the most potentially effective ways to promote energy efficiency and other strategies to reduce greenhouse gas emissions is to increase the cost of activities responsible for emissions to reflect the risks of climate change. The government could increase the price of fossil fuels and other sources of greenhouse gases by imposing charges or fees and at the same time reducing the price of desirable alternatives by providing direct or indirect subsidies. Prices of some relevant commodities, particularly electricity, are already regulated and could be adjusted to promote reduced emissions. Such policies have already been adopted to varying degrees in some states to promote other economic and environmental goals. However, the limitations of economic approaches should also be recognized; other types of policies may be more effective in redressing some market failures, and these can complement policies based on adjusting prices.

Evidence of Market Response to Economic Incentives: Energy Pricing

Proper pricing of energy to reflect the reality of the global warming threat could substantially reduce emissions. It was long assumed (based on historical data) that there was a constant relationship between the rate of growth in energy use and the rate of growth of GNP (Weinberg, 1988). The historical constancy of the relationship was often explained as a consequence of technology and stable or declining fuel prices. The chief flaw in this argument was its failure to anticipate the effects of rising real energy prices. During the century preceding 1973, the relative price of energy had fallen. However, between 1973 and 1985 the price of energy rose, relative to other goods and services, and in accordance with basic economic theory; growth in energy demand slowed, and by some measures declined significantly.

Prior to 1973, U.S. energy demand grew at a rate only slightly less than the rate of growth in real GNP. Had this trend continued, U.S. energy demands would nearly have doubled between 1973 and 1985. Had pre-1972 energy-use trends continued, by 1984 the United States would have been consuming almost 40 percent more energy than it actually did (U.S. DOE, 1987c). But efficiency improvements induced by significant oil price increases enabled the U.S. to hold energy use to 1973 levels while expanding the economy by 40 percent. By one estimate, energy efficiency improvements now save the U.S. economy $160 billion annually.[1]

---

[1] The $160 billion figure is derived by first calculating what total expenditures on energy in 1985 would have been had energy intensities remained constant at 1973 levels and 1985 price levels prevailed, and then subtracting actual expenditures on energy in 1985. For further discussion, see Chandler et al. (1988) and U.S. DOE (1987c).

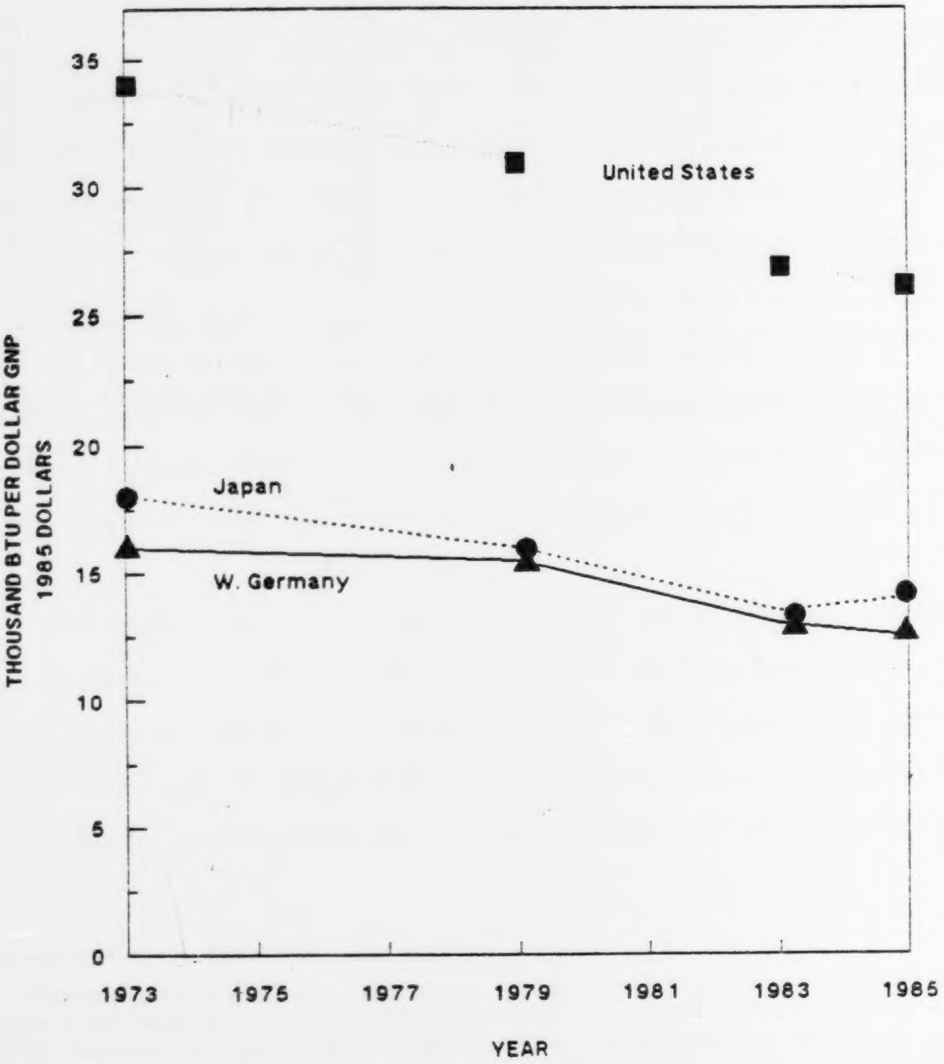
U.S. energy efficiency improved markedly between 1973 and 1985 while energy prices rose markedly (Figure 8-1). However, efficiency improvements in the U.S. and many other industrialized countries have leveled off in recent years. Whereas energy intensity in the nations of the European Economic Community declined 20 percent from 1973 to 1982, the corresponding figure for 1982 to 1986 is 2.4 percent (EEC 1988). One important factor is that oil prices have fallen continuously since 1981. Oil prices dropped precipitously in 1986: World oil prices fell from about $25 per barrel in January 1986 to about $10 per barrel in July 1986. Prices have since fluctuated in the $15 per-barrel range. Adjusted for inflation, gasoline prices in the first half of 1988 were 27 percent less than in 1985 and 48 percent less than in 1980 (Geller, 1988). The rapid decline in world energy prices has slowed the rate of improvement in energy efficiency. This trend is a predictable response to pricing and may continue for some time given Department of Energy forecasts for relatively constant or even declining energy prices in the short term (EIA, 1988).

The performance of other countries suggests that higher energy prices are conducive to greater efficiency. Japan, France, and West Germany, much more dependent on imported oil than the U.S., currently use much less energy per unit of output than does the United States (see Table 8-1). Many developing countries are much less energy efficient than the U.S., in part because they subsidize energy prices.

In recent years, the U.S. has debated and rejected higher oil import fees and gasoline taxes as an instrument of energy policy primarily out of concern that such policies would have significant regional and national macroeconomic impacts (U.S. DOE, 1987; U.S. DOE, 1988). However, without such policies the incentive to purchase more efficient vehicles has declined and the trend has been toward a renewed emphasis on more powerful, less efficient engines (Geller, 1988; Bleviss, 1988).

FIGURE 8-1

ENERGY INTENSITY REDUCTIONS
1973-1985
(Thousand BTU Per Dollar GNP; 1985 Dollars)



Source: Chandler, et al., 1988

TABLE 8-1

Energy Intensity of Selected National Economies, 1973-85

Country	1973	1979	1983	1985	Change, 1973-85 (percent)
	(megajoules per 1980 dollar of GNP)				
Australia	21.6	23.0	22.1	20.3	-6
Canada	38.3	38.8	36.5	36.0	-6
Greece [a]	17.1	18.5	18.9	19.8	+16
Italy	18.5	17.1	15.3	14.9	-19
Japan	18.9	16.7	13.5	13.1	-31
Netherlands	19.8	18.9	15.8	16.2	-18
Turkey	28.4	24.2	25.7	25.2	-11
United Kingdom	19.8	18.0	15.8	15.8	-20
United States	35.6	32.9	28.8	27.5	-23
West Germany	17.1	16.2	14.0	14.0	-18

[a] Energy intensity increased as a result of a move toward energy-intensive industries such as metal processing

Source: IEA, 1987.

Existing federal law gives an additional economic incentive for efficiency through the so-called "gas-guzzler" tax. For 1986 and later models, the law imposes a $500 tax on any car with a fuel economy rating less than 22.5 mpg and a $3,850 tax on models with ratings less than 12.5 mpg. It was originally proposed that the revenues collected be given to purchasers of highly efficient cars in the form of a rebate; however, this proposal was rejected because at the time the beneficiaries would have been almost exclusively buyers of imported cars (see Bleviss, 1988).

Gas-guzzler fees could be used as a potentially more effective and acceptable substitute for gasoline taxes if set equal to the amount that would be collected from a gas tax over the expected lifetime of the automobile. For example, a 50 cents per gallon tax would become a $1,000 excise tax on a 25 mpg car but only $333 on a 75 mpg car. An advantage of this strategy is that, unlike gasoline taxes, it takes advantage of the first-cost sensitivity of consumers in a non-regressive way, taxing new inefficient vehicles the most.[2] The structure of the charge could vary with vehicle class so as not to unduly favor small cars over larger models. The effectiveness of such a system could be enhanced by rebating some of the revenue to buyers of the most efficient models, a concept that now may be more acceptable since several American models rate among the most efficient.

The market for electricity also demonstrates the influence of prices and competition on growth in demand. Until about 1970, the efficiency of new plants was improving and prices of electricity generation were therefore declining, contributing to steady growth in the demand for electricity. From about 1970 through 1982, electricity prices rose mainly as a result of higher fuel costs and interest rates, construction delays, the cost of environmental controls, and the end to significant improvements in generating efficiency. In the last five years prices have been stable or declining as fuel costs stabilized and the amount of new capacity being added slowed in response to the decline in demand (Figure 8-2). The Department of Energy projects continued stable prices until the mid-1990s, followed by modest price increases (EIA, 1987c).

---

[2] First-cost sensitivity refers to the tendency, common to many consumers, to prefer a product that has a low initial cost to a higher-priced alternative which might be much more cost efficient over the long term. In other words, the upfront costs to consumers tend to dominate the purchase decision more than a conventional economic analysis would predict. The use of a hefty excise tax may affect consumer decisions more acutely than would the gasoline expenses for operation of an inefficient vehicle, which occur in smaller amounts and at intervals rather than all at once.

Financial Mechanisms to Promote Energy Efficiency

Since the mid-1970s, the U.S. has accumulated a substantial body of experience with a variety of financial incentives for energy efficiency. Most of these programs have been carried out by state and local governments and utility companies, usually without much publicity but often quite successfully.[3] These efforts suggest the possibilities for more widespread programs in the future.

One of the most popular forms of utility programs is rebates for high-efficiency appliances. A recent survey revealed 59 such programs among U.S. utilities in all parts of the country (Berman et al., 1987; ACEEE, 1988). The majority of these programs are only for residential customers, but more than 20 programs also provide incentives to commercial and industrial customers. Rebates are structured in many different ways; most go only to the purchaser, but some are also offered to retailers. Program coverage varies with differences in demand across the country; some summer-peaking utilities promote both high-efficiency air conditioners to reduce summer demand and heat pumps to increase demand in winter. Rebate amounts frequently vary with the size and efficiency of the appliance, sometimes according to a sliding scale to encourage maximum efficiency. In general, rebate programs appear to be highly cost-effective relative to the costs of new generating capacity. For 33 utilities reporting such data, the median cost of peak demand reduction was $200 per kW saved. (For an example of one unique utility conservation program, see Box 8-1).

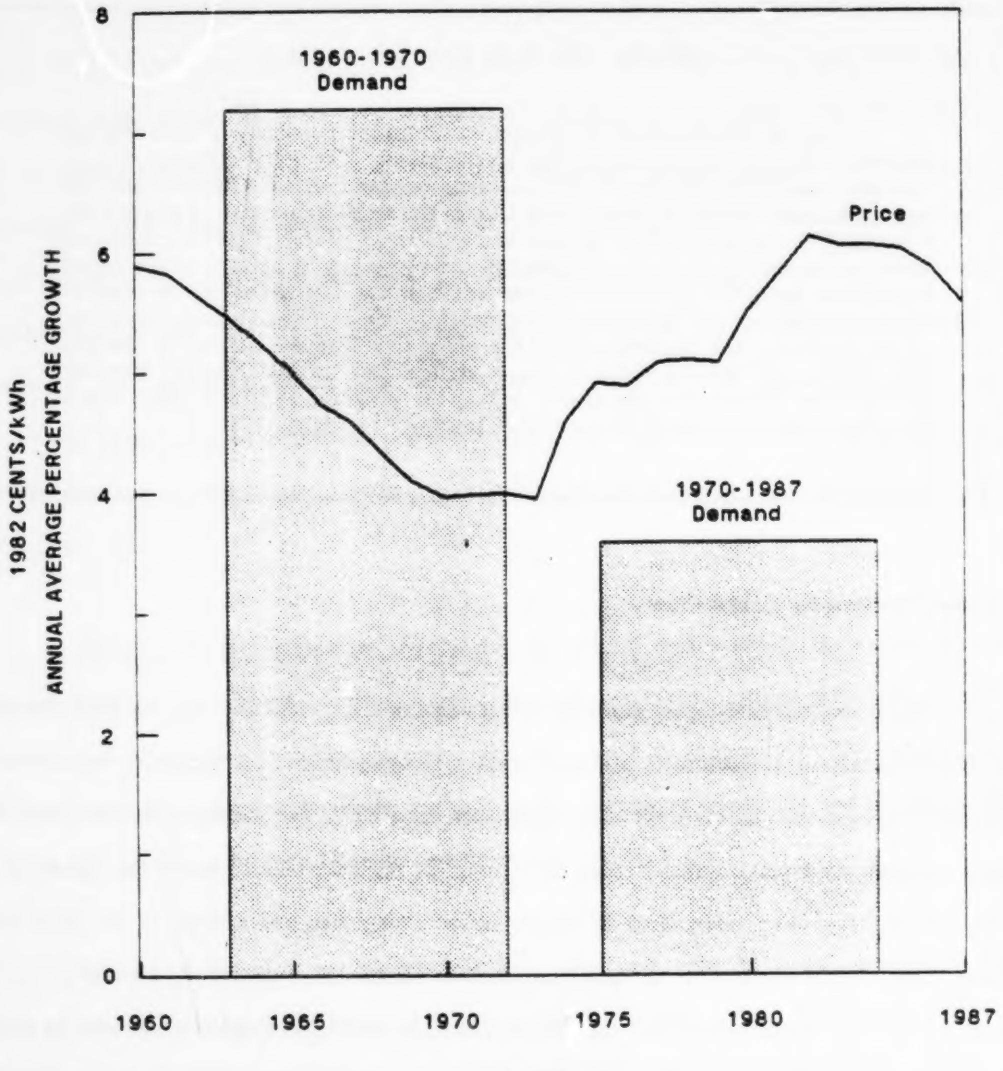
---

[3] The results of these programs have been periodically reported and evaluated by the Electric Power Research Institute, the American Council for an Energy Efficient Economy, and others. See, for example, Berman et al. (1987) and ACEEE (1988).

FIGURE 8-2

U.S. ELECTRICITY DEMAND AND PRICE

(1982 Cents/kWh; Annual Average Percentage Growth)



Source: U.S. DOE, 1988.

Some programs demonstrate the potential for giving economic incentives for energy efficiency to builders. For example, the Bonneville Power Administration's "Super Good Cents" program gives builders a cash grant of $1,000 per house for meeting Model Conservation Standards developed by the Northwest Power Planning Council (Randolph, 1988a).

Box 8-1. The Hood River Experiment

One recent conservation program illustrates the possibility of achieving high levels of efficiency and broad public participation. The Pacific Power & Light Company and Bonneville Power Administration financed what was arguably the most aggressive conservation program in the U.S. in the small community of Hood River, Oregon. The sponsors offered to audit and implement all cost-effective conservation measures in electrically-heated households. In two years, 85 percent of the eligible households accepted improvements, and most of the remainder of the populace received an audit or had previously improved their homes. Space heating levels were reduced to about half the level expected in pre-project forecasts. However, the cost-effectiveness of the program became difficult to evaluate when electricity consumption dropped sharply shortly before the program went into effect due to price increases in excess of 40 percent (Cavanaugh and Hirst, 1987).

Creating Markets for Conservation

The opportunity for highly profitable investments in energy efficiency has not gone unnoticed by some businesses. If consumers are unresponsive to opportunities for profitable investments in conservation, businesses theoretically could make such investments and share the savings, particularly since a technically expert company could avoid some of the uncertainties facing the typical energy user. Such firms, often referred to as energy service companies, did emerge in the early 1980s. These firms offered a one-stop shopping approach to conservation, combining an energy audit to identify opportunities for savings with installation and financing in exchange for a share of the savings for some fixed period. The owner is not required to assume any risk and is guaranteed a bill no more than would have been the case without the improvements. Federal and State governments are testing shared-saving programs to reduce capital spending requirements as discussed in **STATE AND LOCAL EFFORTS** below.

In practice, the energy service concept has proven to be valuable but not a panacea (Weedall et al., 1986). The negotiation and administration of contract terms can be lengthy and expensive. Relatively large savings are necessary to justify the overhead costs, meaning that privately funded energy service companies have generally been most interested in larger projects, such as commercial buildings. One means of expanding the reach of the energy service companies has been the organization of such services by non-profit groups, which can sometimes operate on a lower margin because they do not pay taxes or return a profit and may also be able to obtain below-market-rate financing. On the other hand, the range of permissible activities for such organizations is also usually limited by charter and funding source. Recently, hybrids containing elements of non-profit and for-profit organizations have begun to appear, with possibilities for achieving the benefits of both (Kerwin and Jolin, 1988).

Another innovative approach to reducing the cost of energy service contracting is to pool enough buildings to achieve economies of scale. The Alliance to Save Energy developed a model for this concept after a demonstration program with eight agencies organized by the United Way of Wilkes-Barre, Pennsylvania. However, the project was difficult to implement and the potential for replication remains to be seen (Prindle and Reid, 1988).

Many other financing mechanisms have been tested or proposed (Lovins and Shepard, 1988). Several utilities offer generic rebates for any demonstrated savings; in one area in Manhattan with exceptionally high cost of service the utility offers commercial customers rebates of $500 per kW peak reduction. Another possibility is sliding-scale hookup fees for new buildings, based on the cost of the generating capacity necessary to supply the building's electricity needs (the converse of subsidies for more efficient buildings) (Rosenfeld and Hafemeister, 1988; also see Box 8-2).

Box 8-2. Creating Markets Through Demand Side Bidding

Another emerging approach to promoting markets for efficiency is the demand-side bidding concept. Bidding programs for new capacity have been developed in many states as a means of obtaining low-cost supply additions, a concept that may receive further encouragement from proposed rules now being considered by the Federal Energy Regulatory Commission (FERC, 1988a). FERC has invited comment on the possibility of addressing demand-side bidding, and several states have already implemented such programs. Energy service companies have some potential here since they can achieve some economies of scale. However, large commercial and industrial firms may want to bid themselves rather than share savings (Cole et al., 1988). In 1987 Central Maine Power requested bids for investments producing demand reductions from large industrial customers. The utility offered to pay up to 50 percent of the project cost or a rebate sufficient to reduce the payback to two years, whichever is less; four contracts were produced for a demand reduction of over 11 MW at a cost of $2.5 million.

Limits to Price-Oriented Policies

Economic incentives could play a critical role in reducing greenhouse gas emissions. Nevertheless, there are often practical and political limits to reliance on price-oriented policies. Demand may be very inelastic due to lack of information, the absence of alternatives in the near term, or shortages of capital. Price increases may also have socially undesirable, disproportionate impacts on particular groups or regions. Price increases may also be politically unpopular relative to other policies. Thus, the price necessary to induce change might be so high as to be inequitable, economically impractical, and politically unattractive. Empirical studies illustrate some situations in which increased energy prices have not resulted in nearly the degree of energy efficiency that would be expected from economic calculations. One study at the Energy Analysis Program at the Lawrence

Berkeley Laboratory examined the market for more energy efficient appliances over the period 1972-1980 (Ruderman et al., 1987). The authors found that consumers demand payback periods of two years or less for investing in more efficient household appliances. Except for air conditioners, the implicit discount rates corresponding to these payback periods are much higher than real interest rates or the discount rates commonly used in life-cycle cost analysis of consumer choice (see Table 8-2). The study suggests several factors are responsible for this substantial underinvestment in energy efficiency: lack of information; lack of access to capital to pay for the added first cost; the relatively small savings; a substantial number of purchases of some appliances by builders or landlords who do not pay operating costs; and manufacturers' decisions to limit high-efficiency features to top-of-the-line models that yield higher profit margins.

Studies of small commercial customers and larger industrial customers indicate they also make greater demands of efficiency investments than of alternatives that are considered to be more within their main line of business (Komor and Katzev, 1988; Lovins and Shepard, 1988; Cavanaugh, 1988; Alliance to Save Energy, 1987). Managers of small enterprises may never see the electric and gas bill, have no knowledge of the rate structure for their building, and are largely unaware of which appliances are responsible for most of their bill. Larger companies may demand payback periods of six months to two years for conservation investments, while simultaneously investing in government bonds at an 11 percent interest rate. Utility companies also typically apply investment criteria to new powerplants that are much less demanding than consumer investments to save an equivalent amount of energy (Cavanaugh, 1986).

Some authorities predict that market forces alone are unlikely to prompt continued demand for automobile efficiency improvements due to the declining share of operating costs attributable to fuel as efficiency improves (Figure 8-3). According to an analysis by the Department of Energy, a typical automobile costs over $10,000 and consumes about 370 gallons a year (U.S. DOE, 1988; see

TABLE 8-2

Payback Period in Years for Appliances, 1972-1980

Appliance	1972	1978	1980
Gas central space heater	2.98	2.38	2.21
Oil central space heater	2.33	1.70	1.18
Room air conditioner	5.11	4.77	5.25
Central air conditioner	4.96	4.16	5.18
Electric water heater	0.48	0.41	0.41
Gas water heater	1.50	1.07	0.98
Refrigerator	1.35	1.45	1.69
Freezer	0.60	0.67	0.72

Source: Ruderman et al., 1987.

FIGURE 8-3

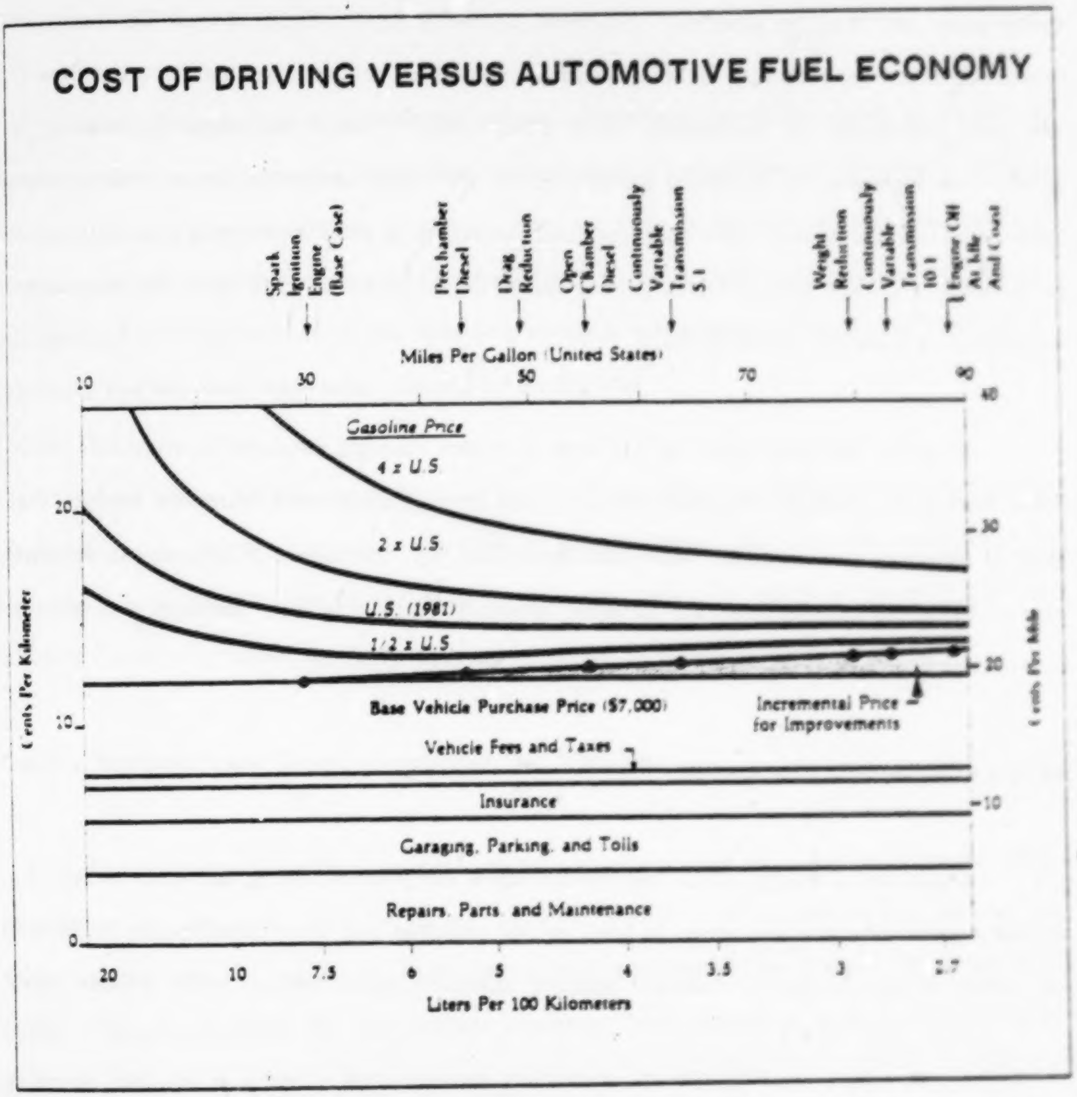


Figure 8.3 The indicated energy performance is based on computer simulations of an automobile having various fuel economy improvements added in the sequence shown at the top of the graph. The base car is a 1981 Volkswagen Rabbit (gas version).

The figure shows that the reduced operating costs associated with various fuel economy improvements are roughly offset by the increased capital costs of these improvements over a wide range of fuel economy.

Source: Goldemberg et al., 1987.

also, Bleviss, 1988; Goldemberg et al., 1987). At $1.10 per gallon, this implies that annual fuel expenses typically represent only about 4 percent of the purchase cost and much less than insurance, maintenance, and financing expenses. The result, according to U.S. DOE, is that "The desire to reduce fuel expenses, even with higher gasoline prices, will not motivate consumers to significantly alter their preferences for automobiles" (U.S. DOE, 1988).[4] Precise evaluation of this effect is difficult; the high visibility of posted gasoline prices may cause some consumers to focus more attention on this cost than on other operating costs. Moreover, at some higher price consumers could be induced to change their preferences, but this price might be so high as to be inequitable, impractical, or politically unacceptable.[5]

Economic incentives alone will not serve to reduce trace-gas emissions to acceptable levels. When markets are unresponsive, there may be a need for regulations on activities and products that result in emissions of trace gases. Many such regulations (e.g., restrictions on imports and domestic uses of CFCs) themselves constitute economic incentives by causing price increases that make it unprofitable to use regulated products or engage in regulated activities.

REGULATIONS AND STANDARDS

Regulation of energy, CFCs, and forestry could complement pricing and other policies for reducing greenhouse gas emissions. In brief, pricing strategies and other government policies may not always induce changes in consumer behavior effectively, either because there is some major market failure or because of an unwillingness to set prices high enough to bring about the desired change in demand.

---

[4] One domestic automotive company reportedly estimates that consumers will seek a 1 mpg improvement in fuel efficiency for every 20 cent increase in gasoline prices (Bleviss, 1988).

[5] One expert has noted that "No aspect of America's energy price system is more peculiar, in comparison with other industrial countries, than the absence of a substantial national sales tax on gasoline" (Nivola, 1986).

Like pricing and economic incentive policies, government regulations should be viewed as simply one tool for promoting the development and adoption of technologies and behavioral changes necessary to reduce greenhouse gas emissions. They are likely to be most effective (and perhaps most acceptable) when they are targeted to specific groups, are no more restrictive than necessary, and are used to complement economic incentives, research and development programs, information programs, and the other approaches outlined in this chapter.

In this section we will consider possible regulatory strategies for existing regulatory programs, which have been adopted for reasons unrelated to climate change, that could be strengthened to either restrict emissions of greenhouse gases or encourage actions to reduce emissions, as well as concepts for new regulatory programs specifically targeted to reduce emissions.

Existing Regulations that Restrict Greenhouse Gas Emissions

The Federal government already has extensive regulations and regulatory programs that limit greenhouse gas emissions, such as its air pollution control laws, restrictions on the use of chlorofluorocarbons, and regulation of investments and rates charged by utilities. There are also energy efficiency standards for automobiles, appliances, and fluorescent lamp ballasts. These programs could be modified to further reduce greenhouse gas emissions.

Regulation of Chlorofluorocarbons

Chlorofluorocarbons (CFCs) are being regulated because of concern about their impact on stratospheric ozone (see discussion in Chapters IV and VII). The potential for introducing substitutes for CFCs to reduce the risks of ozone depletion and global warming has been known for many years. For example, the DuPont Company stated in 1980 that such substitutes could be produced, but the cost would be much higher (DuPont, 1980). Without regulation, however, there was no market for these alternative chemicals and they were not produced. The Montreal Protocol on Substances That Deplete the Ozone Layer, signed in September 1987, provides a framework for global reductions in CFC emissions:

- The use of CFCs-11, -12, -113, -114 and -115 is to be frozen at 1986 levels starting in approximately mid-1989, reduced to 80 percent of 1986 levels in 1993, and reduced to 50 percent of 1986 levels in 1998. The reduction from 80 percent to 50 percent will take place unless the parties participating in the Protocol vote otherwise.
- The use of Halons -1211, -1301, and -2402 is to be frozen at 1986 levels starting in approximately 1992.
- Beginning in 1990, and at least every four years thereafter, the parties will assess the control measures in light of the current data available. Based on these assessments the parties may adjust the control levels and substances covered by the Protocol.
- Each party shall ban the import of the controlled substances (bulk CFCs and halons) from any State not party to the Protocol beginning one year after the Protocol takes effect. The parties shall, in addition, develop a list of products that contain the controlled substances, which will be subject to the same trade restrictions. The feasibility of restricting trade in products manufactured with the controlled substances shall also be assessed.
- Developing countries with low levels of use per capita are permitted to delay their compliance with the Protocol for up to 10 years. The parties also agree to assist developing countries to make expeditious use of environmentally safe alternative substances and technologies.

On August 1, 1988, EPA announced a comprehensive regulatory program for these chemicals that will reduce production and consumption in three phases leading to a 50 percent cut by July 1, 1998 (*Federal Register*, August 12, 1988). The U.S. regulations become effective upon international ratification of the Protocol. In September 1988 EPA Administrator Lee Thomas stated that recent scientific evidence makes it necessary to consider a complete phase-out of these chemicals. The regulatory approach adopted by EPA restricts CFCs by granting limited production rights to the five U.S. companies who manufactured them in 1986, and by restricting imports. This is expected to cause an increase in price and an increasing incentive for CFC users to find substitutes.

EPA was concerned that the added profits for CFC producers could create an incentive to delay the introduction of substitute chemicals. EPA estimated that CFC producers could earn additional profits between $1.8 billion and $7.2 billion by the year 2000. The Agency therefore requested comments on the merit and legality of taxes on CFCs to remove the added profit and potential incentive to delay.

Another concern is that the price rise alone may not be an effective means of reducing demand for some uses of CFCs for which substitutes may be available, but which have a small impact on total product cost. EPA has indicated it will monitor this possibility and will, if necessary, consider product-specific regulations.

Energy Efficiency Standards

Congress adopted minimum energy efficiency standards in 1987 for refrigerators, water heaters, air conditioners, furnaces, and other appliances. The standards take effect on different dates for each product in recognition of differences in product planning and production needs. The law defines standards for different classes and categories of each appliance and does not prevent new features that may increase total energy consumption (see Table 8-3). By one estimate, the standards will reduce peak electricity demand in the year 2000 by an amount equivalent to the output of 22 large powerplants (Geller, 1986). The appliance standards were adopted on the basis of a consensus

TABLE 8-3

Appliance Efficiency Improvements Required by Law

Product	Average Of Those In Use	New Model Average	Best Commercial Model	Estimated Cost-Effective Potential [1]	Potential Savings [2]
		(kilowatt-hours per year)			(percent)
Refrigerator	1,500	1,100	750	200-400	87
Central Air Conditioner	3,600	2,900	1,800	900-1,200	75
Electric Water Heater	4,000	3,500	1,600	1,000-1,500	75
Electric Range	800	750	700	400-500	50
		(therms per year)			
Gas Furnace	730	620	480	300-480	59
Gas Water Heater	270	250	200	100-150	63
Gas Range	70	50	40	25-30	64

Source: Geller, 1986.

---

[1] Potential efficiency by mid-nineties of further cost-effective improvements already under study are made.

[2] Percent reduction in energy consumption from average of those in use to best cost-effective potential.

supported by industry and environmental and consumer groups, demonstrating that a cooperative approach to establish achievable energy efficiency goals is possible. Appliance manufacturers were most interested in preemption of State regulation, while utilities and environmental groups were motivated by energy savings.

The energy efficiency standard for new U.S. automobiles as of 1988 is a corporate average fuel economy (CAFE) of 26 mpg. In September 1988, the Department of Transportation set CAFE standards at 26.5 mpg for the 1989 model year, down from a scheduled increase of 27.5 mpg. Automakers are allowed to meet this requirement by offsetting less efficient (usually larger, more powerful) models with more efficient ones; they may also offset their failure to meet the target in one year with credits gained in prior years. However, mpg ratings of domestic models may not be averaged with those of foreign imports. New-car fuel economy has improved markedly since CAFE was adopted (well over 50 percent since 1973), but its value has been vigorously debated. Critics argue that the gains have been primarily a response to higher prices and that the regulations have imposed substantial costs on manufacturers and consumers. They argue that fuel efficiency is improving due to market pressures and technological innovation, but that if more rapid improvement is desired, it could be promoted more efficiently by higher gasoline taxes to promote demand for more efficient vehicles and encourage turnover of older, inefficient cars (U.S. DOE, 1988; Crandall, et. al. 1986).

However, there is no assurance that market forces alone will produce substantial further improvement in vehicle mileage ratings so long as oil prices are stable or declining in real terms. Higher gasoline taxes would help, but may have to be increased sharply to spur demand for efficiency improvements beyond 30 mpg. Exclusively demand-oriented strategies can leave manufacturers with considerable uncertainty about future markets (Bleviss, 1988). Regulations adopted as a supplement to tax increases could give industry a clear target, reducing the need for hedging strategies that dilute efforts and increase investment costs (Bleviss, 1988).

The CAFE approach also could be improved to both increase incentives for efficiency improvements and meet some industry objections (McNutt and Patterson, 1986). The fleet average concept unduly penalized larger cars, when technologies could allow improvements in all sizes and classes. It required annual improvements, when improvements are made in steps over longer time periods, and then sought to provide flexibility with credits that encouraged a search for administrative exemption rather than long-term improvement. Lower standards were set for light trucks, which further undercut the program. Finally, violations of standards are punishable by court-imposed civil penalties, when equivalent economic incentives could be achieved more acceptably by imposing fees proportional to the noncompliance (Bleviss, 1988).

Air Pollution Regulations

Some greenhouse gases are already regulated as air pollutants because of their effects on human health and welfare. Under the Clean Air Act, EPA sets uniform ambient standards for emissions of carbon monoxide, ozone, nitrogen oxides, and other pollutants and uniform technology-based standards for major new sources of these pollutants. However, States retain responsibility for compliance with the ambient standards, which may require allocating greater responsibility on some sources than on others. States are also free to set more stringent requirements on stationary sources.

The regulatory strategy for control of air pollutants to stabilize greenhouse gas concentrations is not identical to that for achieving compliance with ambient air quality standards. In the latter case, the objective is to stay below threshold levels that effect human health or welfare. However, total, as well as peak, emissions affect the buildup of greenhouse gases, which implies a potentially different regulatory approach. An area barely in compliance with ambient air quality standards at all times may contribute more to greenhouse gas buildup than an area with occasional air quality violations but substantial periods of much cleaner air.

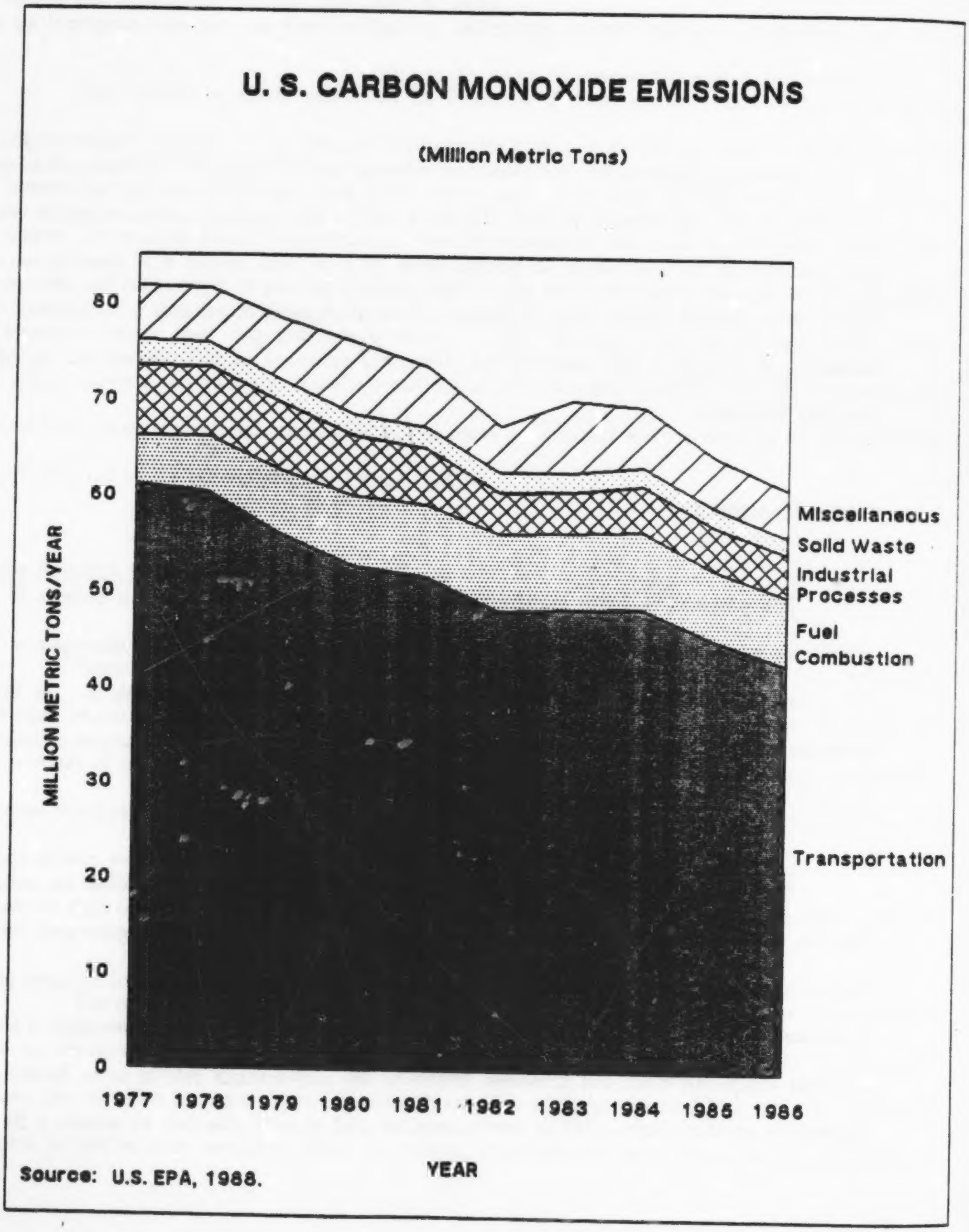
Substantial progress has been made in reducing total emissions of regulated pollutants since the Clean Air Act was adopted in 1970 (U.S. EPA, 1987). For example, carbon monoxide emissions from automobiles dropped about 35 percent from 1970 to 1985 despite a 58 percent increase in vehicle miles traveled (Figure 8-4). Emissions of volatile organic compounds from highway vehicles decreased 48 percent in the same period. However, emissions of NO_x during this period were relatively unchanged.

Waste Management

The problem of waste management illustrates another area in which policies to reduce greenhouse gas emissions may complement other environmental objectives. As discussed in Chapter IV, decomposition of solid wastes is a growing source of methane emissions. In the U.S., governments at all levels have accelerated efforts to promote recycling and reduction of solid wastes for both economic and environmental reasons.

State and local governments have historically been primarily responsible for solid waste disposal. The cost of landfills and public opposition to burning waste has generated substantial interest in recycling and waste reduction. Numerous states have recently adopted stringent programs to reduce the waste stream by a minimum of 25 percent. How this will be accomplished has yet to be made completely clear, but economic incentives will play a major role in some States. Florida adopted an advance disposal fee on every container sold at retail that fails to achieve a 50 percent

FIGURE 8-4



Source: U.S. EPA, 1988.

recycling rate; the fee increases if targets are not met (Carlson, 1988b). California similarly adopted a system of deposit fees with increases scheduled to take effect if goals are not met.

Federal law (RCRA Sec. 4010(c)) assigns EPA the responsibility for ensuring the environmental safety of sanitary landfills. As discussed in Chapter VII, EPA proposed minimum standards on August 1, 1988 that would require gas monitoring stations to detect methane and to plan for its removal, and proposed regulations under the Clean Air Act would require collection of landfill gas at both new and existing landfills. The Agency has also supported a national recycling goal of 25 percent by 1992.

Another source of methane releases discussed in Chapter VII is coal mining. Interest in coalbed methane recovery is increasing for economic reasons, but a this time there are no specific policies to promote such efforts.

Utility Regulation

Regulatory policies also can exert a significant influence on the price and demand for electricity. Electric companies are regulated monopolies whose rates and investments are regulated by State public utility commissions--except for wholesale transactions, which are reviewed by the Federal Energy Regulatory Commission. The structure as well as the overall level of electricity rates is regulated and both influence demand (see Kahn, 1988). For example, some States provide relatively low "lifeline" rates for the initial increment of residential demand to meet the basic energy needs of all customers. The consequence is usually an inverted rate structure, with rates increasing with greater use. Even though rates may be initially set to produce the same total revenue, the result is some reduction in demand because consumers recognize the higher rates associated with greater use. For example, Detroit Edison estimated that a lifeline rate structure imposed in 1981 resulted in reducing demand about 3 percent (Kahn, 1988).

Where the production of electricity to meet peak power needs is more carbon-intensive (e.g., where the marginal fuel is oil and the base fuel has a large percentage of nuclear power), incentives to reduce peak demand and levelize loads may be economically justified and a means of supporting greenhouse gas reductions. With time-of-use metering, utilities can charge rates that more accurately reflect costs, potentially promoting energy efficiency as well as cost savings. This is possible because the costs of generating electricity are not uniform throughout the year; when demand peaks, costs are usually highest because the utility must rely on its most costly units to meet the increased demand. Some utilities in the U.S. and in Europe have tested rate structures that give customers incentives to use electricity at times when costs are low, and conversely, disincentives when costs are high. For example, a recent three-year New York experiment gave customers a one-cent-per-kWh reduction during hours of normal demand, but above a certain threshold level, customers were charged a rate of 40 cents per kWh, several times higher than the usual rate. On average, customers saved 5 to 10 percent annually, reduced their peak period loads over 40 percent relative to the average customer, and expressed strong support for the continuation of the program (Cole and Rizutto, 1988). The metering costs are currently about $500 per house, but the overall program is still expected to produce substantial net benefits. Moreover, it is expected meter costs will drop substantially with large production. (For an example of utility disincentives, see Box 8-3.)

Another significant issue in utility regulation is the creation of competitive markets for the generation of electricity. Federal and State policy has encouraged this concept since the enactment of the Public Utility Regulatory Policies Act (PURPA) in 1978. This law requires utilities to buy power from cogenerators and small renewable energy projects and to pay an amount equal to the

Box 8-3. Disincentives to Utility Conservation

The revenues earned by electric and gas utilities are governed by accounting rules devised to allow utilities to recover operating costs and earn a fair rate of return. These rules were not intended to favor particular types of investments but recent analysis by the Maine and California public utility commissions indicates that they may in fact favor investments in additional supply as opposed to efficiency improvements, even when the latter is much less expensive (Moskovitz, 1988; Cavanaugh, 1988). So long as retail rates exceed short-term production costs, these studies show that, under traditional regulatory practices, utilities will always earn greater profits by selling more electricity, even if the cost of conservation is zero. Allowing utilities to profit from conservation by allowing an equivalent return on such investments does not rectify the situation. Instead, the economic incentive is to do the most costly conservation investments (to achieve the greatest return) with the least impact (to maintain sales). California and Maine have adopted procedures designed to correct these disincentives as one means of encouraging utility interest in demand-side investments.

costs they save as a result. Since the law's adoption, thousands of projects have been developed around the country, despite the absence of a need for new generating capacity in many areas (FERC, 1988c).[6] Federal Energy Regulatory Commission (FERC) compilations indicate cumulative applications from projects equivalent to more than 40 nuclear powerplants (see Table 8-4). FERC is currently reviewing proposed rules to expand the circumstances and type of projects eligible to participate in competitive bidding arrangements (FERC, 1988a, 1988b). FERC has also asked for comment on the possibility of allowing demand-side reduction efforts to compete with additions to capacity.

---

[6] FERC publishes periodic compilations of "qualifying facilities," projects that have formally requested status as entitled to the benefits of PURPA. However, the list is only an approximation of actual activity, since not all projects file such applications; some file after they have already begun operation, and some applications are made for projects that are never completed.

TABLE 8-4

Cogeneration Facilities (No. Filings), [No. of Facilities] and Capacity in Kw

	New		Existing		Both		Total		Qualified Facilities and Initial Capacity	
Coal	(183)	10,419,659	(6)	461,600	(12)	356,272	(201)	11,237,531	[178]	10,948,083
Natural Gas	(1,264)	25,894,776	(41)	1,888,457	(9)	694,671	(1,314)	28,477,904	[1,269]	26,880,678
Biomass	(122)	1,617,390	(18)	570,497	(9)	615,000	(149)	2,802,887	[138]	2,698,802
Waste	(51)	2,432,239	(2)	40,875	(1)	51,000	(54)	2,524,114	[50]	2,450,114
F06/F02	(47)	324,921	(8)	323,700	(1)	5,350	(56)	653,971	[56]	653,971
Other	(38)	1,258,288	(3)	56,500	(1)	62,250	(42)	1,377,038	[39]	1,311,968
Total Cogeneration	(1,705)	41,947,273	(78)	3,341,629	(33)	1,784,543	(1,816)	47,073,445	[1,730]	44,943,616

NOTES:

1. Under §292.202 of the Commission's rules, "Cogeneration facility means equipment used to produce electric energy and forms of useful thermal energy (such as heat or steam), used for industrial, commercial, heating, or cooling purposes, through the sequential use of energy." Topping-cycle facilities first apply the energy input to electric power production; bottoming-cycle facilities first apply the energy input to a useful thermal application. All but 9 filings in this table are topping cycle facilities. Bottoming-cycle and partially bottoming-cycle facilities are listed below:

QF80-6-000	New	Petro Coke	75,000
QF82-100-000	New	Coal	10,000
QF82-207-000	New	Coal/Waste	125,000
QF83-220-000	New	NG, FO	6,000
QF84-134-000	New	Petro Coke	27,300
QF84-192-000	Ex.	NG	910
QF85-572-000	New	Waste/Petro Coke	49,900
QF86-23-000	New	NG	2,700
QF86-800-000	New	Hydrocarbon Coke	3,300

2. "Other" includes cogeneration facilities using nuclear or solar energy sources.

Source: FERC, 1988c

Existing Regulations that Encourage Emissions Reductions

In contrast with the mandatory regulations discussed above, some regulatory programs stress positive incentives for activities to reduce greenhouse gas concentrations. Such programs could be expanded to encourage greenhouse gas reductions.

A prime example of regulatory incentives for actions that reduce greenhouse gas concentrations is the Conservation Reserve Program (CRP) created by the Food Security Act of 1985. The CRP gives up to 50 percent of the cost of establishing approved conservation practices to farmers who agree to take highly erodible cropland out of production for contracted periods of 10 to 15 years. Under Section 1232(c), at least one-eighth of the number of acres placed in the reserve between 1986 and 1990 are to be devoted to trees. As of the sixth signup, ending February 19, 1988, more than 1.5 million acres had been committed to trees--less than a third of the Congressional goal--at a cost to the government of roughly $58 million (Dudek, 1988).

In recognition of the CRP's broader potential for achieving environmental protection, the program was modified in the sixth signup to allow the inclusion of 66- to 99-foot-wide strips of cropland along streams and waterbodies, irrespective of the erosion rate.[7] Tree planting is one allowed use of the land. These so-called "filter strips" provide a buffer zone that absorbs pollutants that would otherwise go into lakes and streams. The Conservation Reserve program offers a possible model and precedent for further cooperation between EPA and the Forest Service to identify opportunities where tree planting may serve multiple-agency goals.

---

[7] Joint Memorandum of the Soil Conservation Service, EPA, Fish and Wildlife Service, and Forest Service on the Conservation Reserve Program Filter Strip Initiatives, April 29, 1988.

Because the CRP program provides such diverse benefits, proposals have been made to expand its scope and coverage. In some States, particularly in the Southeast, aggressive tree planting could become a significant means of offsetting the buildup of carbon dioxide. According to a recent study, most eastern States, with the exception of Florida, appear to have enough erodible acreage to provide the acres needed to offset new CO_2 emissions from electricity production if planted with trees (Table 8-5). Roughly 11-22 million acres of new trees, or about a fourth to one-half of the current CRP goal, would offset projected new fossil-fueled generating plants for the 1987-1996 period if planted with optimum species (Dudek, 1988). By this estimate, the costs are modest relative to other environmental requirements associated with operating powerplants, on the order of 0.5 cents per kilowatt-hour.

New strategies to promote tree planting may avoid some of the limitations and complications created by the CRP program, which must identify farmers willing to withdraw farmland and which restricts the land for a period less than the time many trees require to reach maturity. Utility companies and large industrial coal users may also wish to sponsor tree planting. The Forest Service reports that southeastern States--where most timber industry investments have occurred in the past two decades--must replant and manage their dwindling forests to allow its timber industry to keep growing (USFS, 1987).

The Food and Security Act has another provision that demonstrates the potential use of regulations to promote environmental goals. Under Section 1221, any farmer who produces an agricultural commodity on a wetland converted to agricultural use after the effective date of the Act may become ineligible for many forms of USDA financial assistance. The restriction applies to all of the farmer's land, not only the converted wetland area. The impact of the program obviously depends on the value of the financial assistance, which in turn varies with commodity prices, but the precedent is important (see Tripp and Dudek, 1986).

TABLE 8-5

Erodible Acreage Available to Offset CO_2 Emissions From Electricity Production

State	Megawatts (MW)	CO_2 Emission (10^3 tons)	Erodible Acres (10^3 acres)	Offset Acreage (10^3 acres)	Percent (%)
Alabama	1,557	10,458.4	2,558.8	697.2 - 2,091.6	27.2 - 81.7
Arizona	710	4,900.3	187.1	326.7 - 980.1	>100
Colorado	899	6,204.7	6,480.1	413.6 - 1,240.8	6.4 - 19.2
Florida	2,678	15,136.3	670.2	1,009.1 - 3,027.3	>100
Georgia	1,641	11,325.9	3,072.7	755.1 - 2,265.3	24.6 - 73.8
Iowa	50	201.2	17,833.7	13.4 - 40.2	0.1 - 0.3
Indiana	1,600	10,179.6	5,244.2	678.6 - 2,035.8	12.9 - 38.7
Kentucky	1,095	7,557.5	2,412.7	503.8 - 1,511.4	20.9 - 62.7
Louisiana	540	3,727.0	2,171.0	248.5 - 745.5	11.4 - 34.2
Maryland	753	4,870.3	602.7	324.7 - 974.1	53.9 ->100
Minnesota	1,251	8,634.2	10,102.0	575.6 - 1,726.8	5.7 - 17.1
Missouri	1,005	6,792.4	7,223.7	452.8 - 1,358.4	6.3 - 18.9
Mississippi	250	1,725.5	3,009.9	115.0 - 345.0	3.8 - 11.4
North Carolina	690	4,762.3	2,476.4	317.5 - 952.5	12.8 - 38.4
Nevada	1,865	12,469.0	79.1	831.3 - 2,493.9	>100
Ohio	1,300	8,972.4	3,799.8	598.2 - 1,794.6	15.7 - 47.1
Oklahoma	470	2,754.6	3,795.2	183.6 - 550.8	4.8 - 14.4
Texas	5,515	38,063.5	20,417.2	2,537.6 - 7,612.8	12.4 - 37.2
Utah	814	5,577.8	392.6	371.9 - 1,115.7	94.7 ->100
Wisconsin	60	414.1	4,015.6	27.6 - 82.8	0.7 - 2.1
Total	24,743	164,727	96,544.7	10,981.8 - 32,945.4	11.4 - 34.2

Source: Dudek 1988.

Another example of regulatory incentives for actions to reduce greenhouse gas emissions is higher rates of return in some States for utility investments in efficiency or renewable energy. Utilities are also sometimes allowed to choose whether to amortize their investment and receive a return or recover their expenses in the first year. Some States have also adopted revenue adjustment provisions to prevent reductions in utility profits as a consequence of utility-sponsored conservation programs (Cavanaugh, 1988; Moskovitz, 1988).

There are some practical questions to be answered before attempting a large-scale program to offset carbon emissions with trees, particularly if implemented on an international basis. For example, there may be difficulty counting net "new" trees in a developing country undergoing deforestation; there must be assurances that the trees are properly cared for and not cut down prematurely. Similarly, counting net energy reductions may be difficult since a factory may have intended to make improvements in any case.

Despite these concerns, the offset concept offers some advantages that make it worthy of further consideration. First, it can be targeted to achieve greenhouse gas reductions, unlike energy regulations, which may not always reduce carbon-intensive fossil fuels. Second, it is consistent with efficiency and innovation by allowing each developer the flexibility to seek out the least expensive means of reducing his emissions. Third, it can be implemented in a way that promotes international cooperation by allowing reductions to be achieved in developing countries where they can be accomplished most cheaply and also contribute to development. Eligibility for offsets could be limited to countries that join in an international greenhouse agreement as an incentive for participation.

RESEARCH AND DEVELOPMENT

Further research and development (R&D) will be necessary to bring about widespread use of many of the technologies and strategies reviewed in Chapter VII. As discussed below, in some areas substantial programs are already in place, while in others existing priorities may not be entirely consistent with the objective of stabilizing greenhouse gas emissions.

Research programs can serve several different purposes. In some cases, such as finding more efficient methods for producing steel and photovoltaics, basic research is needed. In other areas technologies are nearly commercially ready but their introduction could be accelerated through testing and demonstration. Research is important to improve policies and programs as well as hardware; for example, the U.S. has acquired a great deal of experience with energy conservation programs over the last decade that has yet to be fully evaluated and summarized for use by public and private authorities.[8]

The importance of government support for R&D is widely accepted; industry often has only a weak incentive to pay for research that will be of widespread benefit, or that is long term and high risk (U.S. DOE, 1987c). However, government can create incentives for greater industry efforts. Special efforts are also needed to develop technologies suitable for use in developing countries where local needs and resources may dictate very different solutions.

---

[8] One excellent source of information on technologies, programs, and policies on energy efficiency in buildings is the biennial proceedings of the summer study program organized by the American Council for an Energy Efficient Economy (ACEEE, 1988).

Energy Research and Development

The energy R&D budget is important from a greenhouse perspective in both its total amount and its relative priorities. Research to promote the more efficient use of all forms of energy is desirable from the standpoint of greenhouse gas emissions, as is research to reduce the cost of renewable and nuclear energy relative to fossil fuels. Since FY 1981 annual appropriations for energy R&D have declined from $3.4 billion to roughly $1.4 billion in FY 1988. An examination of R&D expenditures in other western industrialized countries suggests that their research budgets have tended to fluctuate less than those of the U.S.; as of 1986 the U.S. ranked last among OECD member countries in the percentage of GNP devoted to energy R&D. However, U.S. expenditures still ranked first in absolute terms (Table 8-6).

Priorities among energy sources have also shifted during the 1980s as research on renewables and conservation has declined more than research in other areas (see Figure 8-5). The Clean Coal Program is by far the largest energy R&D initiative this decade; President Reagan requested $525 million for FY 1989 and $1.775 billion for FY 1990-1992. The intent is in part to improve the efficiency of coal use, but equally important to expand the market for coal here and abroad--an objective that would unavoidably increase carbon emissions relative to other fuels used with equivalent efficiency (U.S. DOE, 1987c; see also, National Coal Council, 1987).

The analysis presented in earlier chapters of this report suggests that research priorities may have to be redirected in order to stabilize greenhouse gas emissions. Several prime objectives are to reduce the demand for fossil fuels for transportation, reduce the energy intensity of basic materials production, particularly steel and cement, and improve the efficiency of biomass use for energy. The prospects for research to improve light vehicle fuel economy are discussed in more detail below.

TABLE 8-6

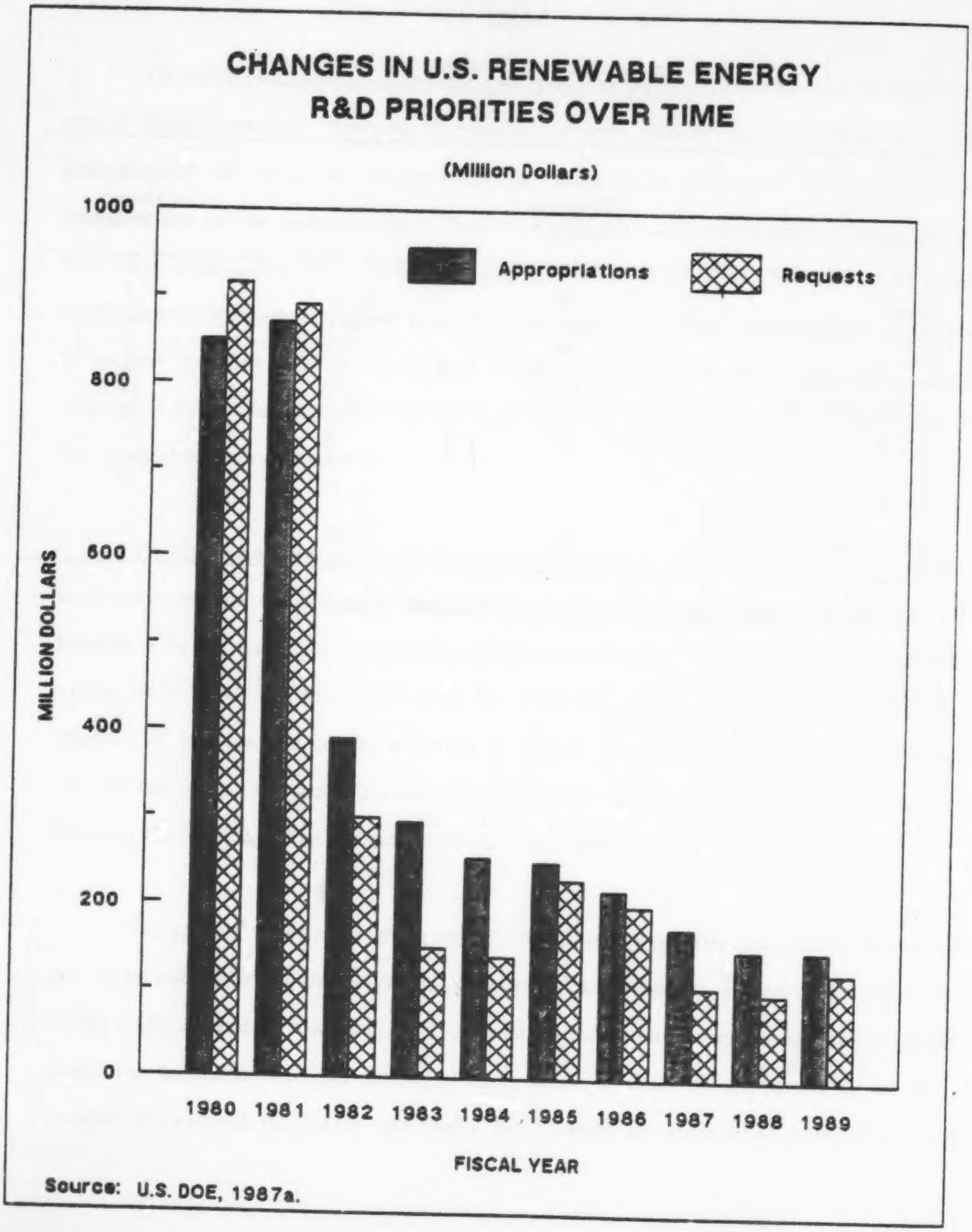
Government Efficiency Research and Development Budgets in OECD Member Countries, 1986

Country	Efficiency Budget	Total R&D Budget	Efficiency as Percent of Total
Japan	78	2,311	3
United States	275	2,261	12
Italy	48	761	6
West Germany	21	566	4
United Kingdom	43	378	11
Canada	34	336	10
Sweden	29	79	37
Greece	0	15	0
Denmark	5	14	36
Total OECD[1]	622	7,133	9

[1] Total includes minor additional expenditures. Excludes France.

Source: IEA, 1987.

FIGURE 8-5



Source: U.S. DOE, 1987a.

Based on projections supplied by automobile manufacturers, the Department of Energy recently estimated that U.S. fuel economy will rise modestly from 27.1 mpg in model year 1988 to 32 mpg in 1995 (U.S. DOE, 1988). U.S. DOE recommended against any action to spur the development or introduction of more efficient vehicles, instead suggesting the use of alternative fuels and increased domestic production of petroleum (U.S. DOE 1988; 1987c). However, these alternatives could exacerbate the greenhouse problem, particularly if alternative fuels were coal-derived (see Box 8-4).

Total federal spending on R&D is not the only measure of success. Some studies suggest that the variations in funding levels and priorities in U.S. R&D efforts have reduced their effectiveness relative to more steady and long-term programs such as those in Japan (Flavin, 1988; Chandler et al., 1988). Federal R&D support may no longer be as important for technologies reaching commercial competitiveness, such as photovoltaics; low energy prices have become a more critical obstacle (Carlson, 1988a). The largest improvements in energy efficiency often result from changes in processes or products that serve multiple purposes; reduced energy costs may be only a secondary consideration (OTA, 1983). Narrowly-focused energy conservation programs may not effectively address this objective. One alternative is to establish research centers for energy-intensive industrial processes. Such centers could research multiple improvements on a cooperative basis with industry and academia, an approach currently incorporated in the Combustion Research Program operated by Sandia National Laboratories (Chandler et al., 1988).

Federal programs are also not the only large source of energy R&D support. Several states, notably New York, California, and North Carolina, have created State agencies to support energy R&D (see **STATE and LOCAL EFFORTS**, below). Private sector support is also large; the utility-supported Electric Power Research Institute and Gas Research Institute both have annual budgets

Box 8-4. Light Vehicle Fuel Economy R&D

Prototype vehicles designed by Toyota and Volvo have already demonstrated that it is technically possible to produce full-sized vehicles with fuel economy of 70 mpg or better, as discussed in Chapter VII. Recent developments in materials technology and other areas suggest that even this level will be greatly exceeded in the near future. The problem therefore is less one of basic science than it is lack of incentives for product development to reduce costs. The relatively low price of oil has diminished incentives to invest in improved efficiency unless it is associated with other features considered more marketable. This is true both in Japan and Western Europe, as well as in the U.S., since the price of oil has declined even more rapidly in these countries due to the relative decline in the value of the dollar.

Barring another large rise in oil prices or some significant government policy intervention, it seems unlikely to expect that consumers will demand, and that manufacturers will produce, vehicles with much higher fuel economy. Indeed, there is some evidence that fuel economy (particularly in U.S.-made vehicles) will stagnate or even decline in the near term due to market demand for larger models and increased acceleration and performance capabilities (Bleviss, 1988).

in excess of $100 million, and some of these organizations give high priority to research on efficiency improvements.

Another important consideration is the allocation between basic science and more applied research. The former has received highest priority but demonstration and technology transfer programs can accelerate acceptance of innovative ideas that have been proven on a small scale but not yet widely adopted. The Department of Energy now supports some technology transfer activities for conservation (U.S. DOE, 1987c) and full-scale demonstration of clean coal technologies to provide "proof-of-concept" experience (*Clean Coal Synfuels Letters*, August 26, 1988, pp.3-4; U.S. DOE, 1987c). Some of the technologies with greatest potential to reduce greenhouse gases, such as advanced gas turbines (see Chapter VII), also could benefit from full-scale demonstration and evaluation (Williams, 1988).

Energy R&D should also include examination of policy and program issues (IEA, 1987). One very critical question is why so many consumers often fail to invest in energy conservation measures despite very high rates of return; this behavior appears to be irrational in economic terms (Kempton and Neiman, 1987; Aronson and Yates, 1985). Consumers also respond differently to loans, rebates, and other subsidies even though they have roughly equal cost to the government.

Another research need for policy purposes is a more detailed data base on international sources of greenhouse gas emissions. The compilation of such data should be an initial goal of the recently formed Intergovernmental Panel on Climatic Change.

Global Forestry Research & Development

The benefits of trees for storage of carbon are widely accepted, but the elements of a large-scale forestry program to stabilize greenhouse gas emissions have yet to be fully described (see discussion in Chapter VII). Such a program would seek to maximize global vegetation and storage of carbon. The steps necessary to accomplish this objective may not be entirely consistent with the emphasis and goals of existing governmental and commercial forestry research programs. The preservation of tropical forests, for example, is a critical international environmental problem with considerable impact on global climate change. However, this effort may not be the most cost-effective way to increase net global forest cover, because the underlying causes are often closely related to deeply-rooted social ills that require very long-term solutions. Large-scale plantation forestry is one alternative, but the economic criteria used in commercial forestry may also have little relationship to maximizing carbon storage.

Traditional forestry research priorities have not emphasized conservation. Recent reviews of forestry research in tropical countries conclude that most projects have focused on the creation of large-scale industrial plantations and other activities to promote the improved industrial use of timber (FAO, WRI, World Bank, and UNDP, 1987a; FAO, 1988). According to the Tropical Forest Action Plan prepared by an international task force, forestry has not received the large-scale, targeted research support devoted to agricultural study of plant breeding and the development of improved crop varieties. The Plan proposed to begin responding to these needs with a five-year, $1 billion research program.

Efforts to date indicate that forestry research can produce markedly higher yields through genetic improvement and better management practices. For example, a Brazilian paper company was able to double yields from 33 to 70 cubic meters per hectare per year through genetic selection and cloning (WRI, World Bank, and UNDP, 1985). Research and demonstration can also help promote sustainable management practices; an AID-funded village woodlot project in Thailand shows that planting fuelwood species can be profitable and environmentally protective (U.S. AID, 1987).

More research on managing public lands, pricing public resources, and other policy aspects of tree planting is also needed. For example, government policies in both the developing and industrialized world have been a major source of pressure on tropical forests, but this relationship has not been thoroughly studied. Excessive consumption of forest products has also sometimes been encouraged by underpricing of public resources in some developing countries (see **CHAPTER IX**).

Research to Eliminate Emissions of CFCs

Industry is now making substantial effort to reduce or eliminate emissions of CFCs as discussed above (U.S. EPA, 1988; Cogan, 1988). However, existing regulatory incentives may not be adequate to assure that all users of CFCs will make a serious effort to find substitutes. The demand for some uses of CFCs, such as automotive air conditioning, is highly inelastic because the cost is very low relative to the total cost of the product and there are no obvious short-term alternatives (*Federal Register*, August 12, 1988). EPA is considering regulatory changes to address this problem, but also is attempting to bolster industry interest in alternatives through a program of cooperative research on promising technologies (U.S. EPA, 1988; Claussen, 1988). Such efforts could be expanded as part of an effort to phase out all CFC emissions as soon as possible and could serve as a model for programs to reduce emissions of other greenhouse gases.

INFORMATION AND TECHNICAL ASSISTANCE PROGRAMS

The government can facilitate the development and adoption of new technologies and strategies through many forms of information and technical assistance programs. These efforts complement research, pricing, and other policies by making consumers more aware of the value of energy conservation and therefore more likely to respond to investment opportunities. Information programs can serve to improve consumer understanding of the significance of energy costs, which are often underestimated because they occur over time. For example, many consumers do not know the relative energy cost of home appliances or that the cost of operating a refrigerator over its lifetime will be greater than the first cost. Information coming from the government is also frequently perceived to be more credible than similar information coming from utility companies or other private firms (Kempton and Neiman, 1987).

Information and technical assistance programs take a variety of forms to serve a range of specialized purposes. Within the Department of Energy, R&D results are disseminated to potential users through "technology transfer" programs (U.S. DOE, 1987c). One element of this program is the National Awards for Energy Innovation, which annually recognizes outstanding achievements in conserving and producing energy.

U.S. DOE also operates several energy information services for different audiences (U.S. DOE, 1987b). The Conservation and Renewable Energy Inquiry and Referral Service (CAREIRS) serves the general public through a toll-free telephone number and refers technical questions to one of several hundred laboratories and expert agencies. In FY 1987, CAREIRS responded to more than 40,000 inquiries. General information on energy production and consumption is also available through the National Energy Information Center and the Solar Technical Information Program. More specialized assistance is provided by the National Appropriate Technology Assistance Service (NATAS), which will help evaluate new technologies and suggest approaches to commercialization.

The Federal government has also provided consumers detailed information on the comparative energy cost of new cars and appliances through mandatory labeling requirements. These programs improve market forces by making it easier for consumers to make decisions about the value of more expensive but more efficient models.

There is no standardized or widely-accepted system for communicating energy cost information for homes and buildings, which may be partly responsible for the slow rate of improvement in this sector (Chandler et al., 1988; Hirst et al., 1986, Alliance to Save Energy, 1988). For example, such a system could be used by lenders to evaluate the expected energy cost of a home as a factor in loan amounts, creating an incentive to improve energy efficiency. Such a system is used on a limited basis now by the Federal National Mortgage Association (U.S. DOE, 1987c). Another model is in use by 12 banks in Seattle (Hirst et al., 1986).

Several Federal information programs directed to small-scale energy use have been gradually curtailed but still operate in many states. One is the Residential and Commercial Conservation Program, which requires electric and gas utilities to offer home energy audits to their customers for a minimal charge. The program was not promoted effectively in most parts of the country and participation has typically been very low, although a few states achieved notably better success (Hirst et al., 1986). The Energy Extension Service provides a small amount of Federal support for State energy information programs and technical assistance programs targeted to individuals and small energy consumers.

Another approach to improving consumer awareness of energy costs is through the introduction of technology that continually reports electricity costs. Advances in microelectronics and communications now make it possible to provide such information for a cost that could be offset by savings achieved through better energy management and shifts in time of use, while at the same time more closely tracking marginal costs (Peddie and Bulleit, 1985; Rosenfeld, 1985).

Federally-supported programs have also helped support development of computer models and other analytical methods for evaluating the energy use from new residential and commercial buildings. These analytical tools can be used by designerd to lower the energy use of buildings and as a basis for calculating energy use for purposes of minimum standards and incentive programs (Vine and Harris, 1988). Computer models of building energy use were a key product of the Federal Building Energy Performance Standards. The Standards began as a mandatory Federal regulatory program in 1976 but Congress subsequently amended the law to require only voluntary guidelines. The standards have yet to be released in final form, but much has been learned in the process and interim products have been used by industry and government. The Federal government could facilitate use of the final rules by providing additional technical assistance such as materials on compliance methods (U.S. DOE, 1987c, Chandler et al., 1988).

The integration of research, technical assistance, and public information has a long and productive tradition in Federal agriculture programs. The Federal budget for such activities is about $3 billion annually, and as of 1984 there were over 3,500 specialist extension agents and over 11,000 county agents (OTA, 1986). As discussed in Chapters IV and VII, modifications in some farming practices, such as selection of crop varieties and fertilizers, water use, and disposal of crop residues may inhibit greenhouse gas emissions, although more research is needed to establish the efficacy of such changes. As our understanding of agricultural sources of greenhouse gas emissions improves, extension activities could be used to teach farmers how to reduce their emissions.

Information and technical assistance is also an important function of bilateral aid, as discussed in **U.S. Bilateral Assistance Programs** (Chapter IX).

CONSERVATION EFFORTS BY FEDERAL AGENCIES

The Federal government is the single largest consumer of energy in the United States, accounting for 2.5 percent of total energy consumption (U.S. DOE, 1987a).[9] The annual energy budget for over 500,000 Federal buildings and facilities is about $4 billion, plus another $2 billion for Federally-assisted housing. A Federal Energy Management Program was established 12 years ago to provide leadership in reducing these costs and has achieved some success. According to U.S. DOE, cumulative energy savings over the past 12 years are nearly 1.6 Quads, equivalent to about $6.5 billion in savings (U.S. DOE, 1987a; see Table 8-7). In FY 1985 a 10-year performance target for improving the energy efficiency of Federal buildings ended, having attained a 16.6 percent reduction in energy per square foot relative to a 20 percent target.

The government could use its buying power to test and demonstrate energy conservation and alternative energy sources. Government procurement could help demonstrate new products, acting as an incentive for manufacturers worried about the lack of a market and consumers worried about being first-of-a-kind purchasers (Goldemberg, 1987). The Department of Energy expressed support

---

[9] Expenditures on energy in FY 1987 were over $8 billion, or 0.8 percent of the Federal budget.

TABLE 8-7

Federal Energy Expenditures and Cost Avoidance FY 1975-FY 1987

	Annual Energy Cost ($ Million)	Annual Energy Use Reduction Rel. to FY 1975 (BBTU)	Average Annual Energy Cost ($/MBtu)	Annual Energy Cost Avoidance ($Million)
Buildings and Facilities				
1975	1,812.453	---	2.107	---
1976	1,888.673	58,080.4	2.355	136.779
1977	2,162.395	51,847.4	2.675	138.692
1978	2,286.054	66,013.3	2.879	190.052
1979	2,636.361	77,885.9	3.370	262.475
1980	3,168.399	97,947.3	4.157	407.167
1981	3,713.200	99,466.9	4.882	485.597
1982	3,804.965	92,207.3	4.955	456.887
1983	3,863.248	98,559.4	5.073	499.992
1984	3,919.356	64,706.3	4.928	318.873
1985	4,054.799	27,131.1	4.868	132.074
1986	3,828.608	50,877.7	4.731	240.702
1987	3,941.605	6,465.6	4.617	29.852
Total				3,299.142
General Operations				
1975	2,697.494	---	2.578	---
1976	2,310.695	129,389.8	2.520	326.062
1977	2,594.787	115,884.7	2.789	323.202
1978	2,710.483	139,408.6	2.989	416.692
1979	3,705.588	112,222.9	3.967	445.188
1980	6,195.928	94,910.6	6.513	618.153
1981	8,239.325	33,191.0	8.182	271.569
1982	9,828.685	6,669.7	9.454	63.055
1983	8,743.907	9,260.1	8.432	78.081
1984	7,728.081	18,506.1	7.258	134.317
1985	6,336.706	49,557.8	6.358	315.088
1986	4,006.669	63,407.1	4.077	258.511
1987	4,348.108	26,606.8	4.264	113.451
Total				3,363.369
All Energy Total				6,662.511

Note: This table incorporates revisions to previously published energy consumption and cost data submitted to DOE by Federal agencies. Energy costs for FY 1975 - 1981 are estimated, based on data provided by the Defence Fuel Supply Center and the DOE Energy Information Administration (EIA). Energy costs for FY 1982 - 1987 are based on annual reports submitted to DOE by Federal agencies.

Source: U.S. DOE, 1987a.

for this role in the 1987 *Energy Security* report to the President: "The Federal Government should lead by example in testing and adopting cost-effective technologies that use energy more efficiently, especially those that minimize future reliance on insecure supplies of oil" (U.S. DOE, 1987c).

According to the U.S. DOE, a major obstacle to Federal conservation efforts was recently addressed through a change in Federal law. Conservation investments, although cost-effective, may require a substantial initial investment in order to achieve energy and cost savings over the long term (U.S. DOE, 1987a). Agencies may now legally "share the savings" from investments in conservation through contracts for up to 23 years with companies that supply the necessary equipment or services in lieu of paying the full capital cost upfront. Several states already have such programs, which can serve as demonstration programs for other levels of government and the private sector and may facilitate future Federal efficiency investments. Texas has implemented an energy performance audit program for 18 major universities enforced by a potential 10 percent withholding of administrative funds. The audit includes a review of the energy management program, including procedures for tracking and monitoring, use of audit activities, capital outlays, and professional training programs. The entire program has been highly cost-effective and in addition served to increase upper management awareness of the energy management opportunities under their control (Verdict, 1988).

STATE AND LOCAL EFFORTS

State and local governments can make an important contribution to the reduction of greenhouse gas emissions. Much environmental regulation and energy policy are to a considerable degree State and local responsibilities. For example, State public utility commissions oversee decisions about the need for new generating capacity and the choice of fuel and can exercise their discretion to promote or discourage particular fuels to promote environmental objectives (ABA, 1980; Randolph, 1988b).[10]

A growing number of States have adopted programs to reduce costs and growth in electricity demand through comprehensive planning and conservation efforts supported by electric utilities. There is evidence that the potential impact of such programs is very large and could allow substantial displacement of fossil-fuel generating capacity in the future. At least 10 States have statutory requirements and policies requiring that utilities examine efficiency investment opportunities as part of a "least-cost" plan (Machado and Piltz, 1988). However, in recent years some utilities have reduced their commitment to conservation and renewed efforts to promote new demand for electricity in order to reduce the costs of excess capacity.

One of the most comprehensive and thoroughly evaluated programs is in the Pacific Northwest. The Northwest Power Planning Council, a regional planning agency created by Congress in 1980, must by law evaluate conservation as a potential resource comparable to generation, and may not support new plants until after first undertaking less expensive demand-side measures. In cooperation with the Bonneville Power Administration, the region spent over $800 million on conservation between 1979 and October 1987. The Council concluded that its conservation programs had achieved energy savings at costs ranging between 1.9 and 2.9 cents per kilowatt-hour, much less than the cost of generation. The Council has undertaken some conservation programs despite a power surplus because of the potential "lost-opportunity" resource if, for example, new buildings are constructed without cost-effective conservation measures. Savings from improving the efficiency of new buildings alone are estimated at $70 million over 20 years (NPPC, 1988).

---

[10] For example, Washington offers utilities a higher rate of return on investments in renewable energy systems, while Texas requires that renewable energy be considered first when a utility seeks to add new capacity and also requires retail wheeling (use of transmission lines) for renewable energy generators under 10 MW whose owners wish to sell power to non-utilities.

A recent Michigan study focused on opportunities to improve efficiency in the residential sector (Krause et al., 1988). The study, done by the Lawrence Berkeley Laboratory, examined the technical and economic potential for electricity conservation. Some of the key findings were that 3400 GWh/year, or 680 MW of baseload equivalent, can be reliably saved by 2005. This is about 29 percent of the forecasted demand for this date and is about two-thirds of the technical potential (Figure 8-6). The result implies a steady decline in overall residential electricity demand of about 1 percent per year over the next 20 years. Most of the projected savings could be purchased at a cost of less than 3 cents per kWh assuming utilities pay for the full extra first costs of consumer investments; the average cost is about 1.1 cent/kWh, in contrast with short-run marginal costs in Michigan of about 3 cents/kWh and much higher costs for new capacity. The greatest savings are from improving the efficiency of lighting, water heating, and refrigerators. The net present value of implementing these savings over 20 years at a 7 percent discount rate would be $545 million.

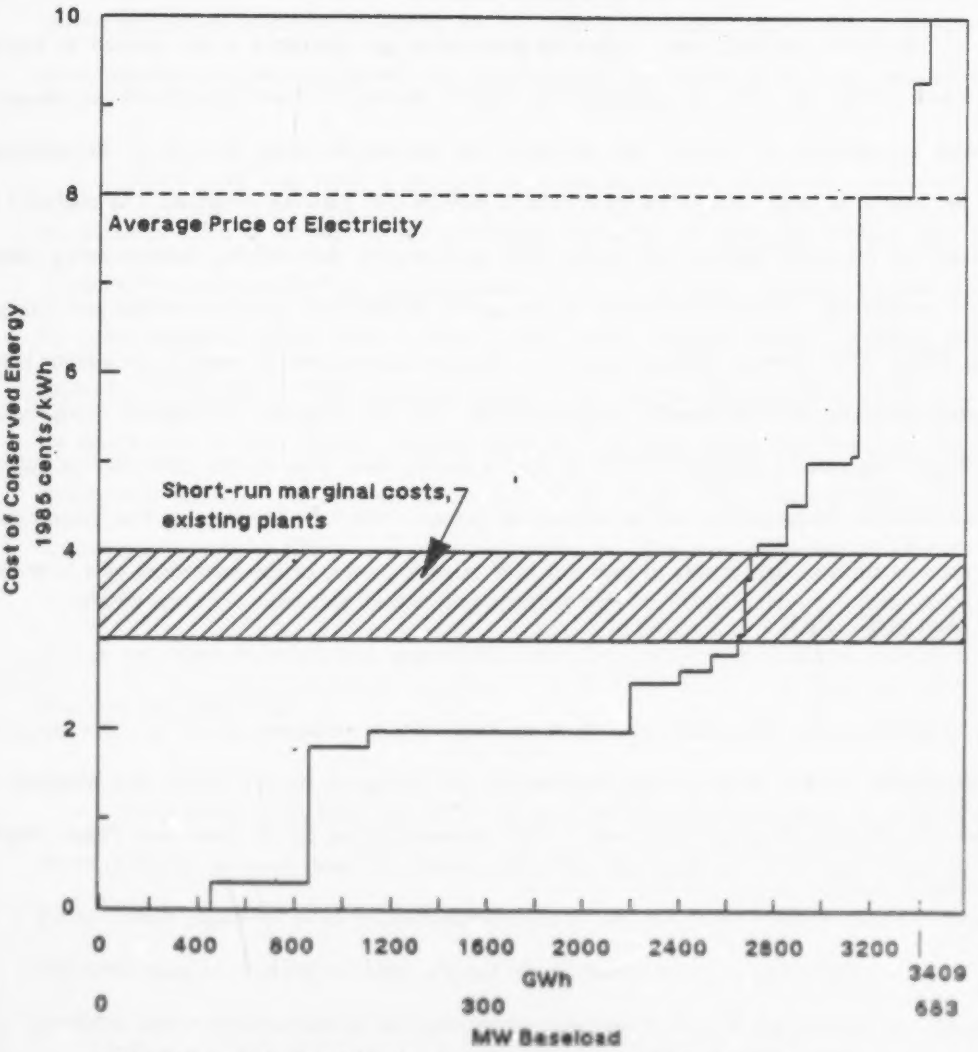
Some States have undertaken impressive programs to develop alternative energy technologies suited to their climate and energy needs. The North Carolina Alternative Energy Corporation (AEC), for example, is funded by voluntary contributions from electric utilities recovered from ratepayers (Harris and Kearney, 1988). The AEC has contributed almost $6 million to projects that test or demonstrate either conservation, load management, or renewable energy technologies. New York and California are among the other States with substantial energy research programs.

Local governments also undertake many relevant activities. One traditional local government function is to establish building codes and land use regulations. Some local governments have implemented stringent energy conservation requirements for new housing. For example, Tacoma, Washington, estimates that compliance with its code adds only $2,000 to the cost of a new home but saves electricity at a cost equivalent to 2 cents/kWh (much less than any new generation) and offsets

FIGURE 8-6

COST OF POTENTIAL RESIDENTIAL ELECTRICITY CONSERVATION IN MICHIGAN BY 2000*

(1985 cents/kWh)



* Based on analysis of territories served by Consumers Power and Detroit Edison companies and assuming a 7 percent discount rate.

Source: LBL, 1988.

the need for 1 MW of generation (Randolph, 1988a). Seattle, Santa Monica, and several other cities have worked out cooperative arrangements with their utilities in which the utility provides audits or other services on a reimbursable basis--sometimes at a profit (Randolph, 1988a). Two California cities, Davis and Berkeley, require compliance with minimum residential energy standards as a condition for the sale of a home (Randolph, 1988a).

The State and local role in limiting greenhouse gas emissions is not limited to energy regulation. Other state and local authority that could be exercised to lower greenhouse gas emissions includes management of landfills and regulation of existing stationary sources of air pollution. Another source of large, short-term opportunities may be tree planting programs. As discussed in Chapter VII, urban tree planting can reduce local temperatures, thus reducing summer energy needs for air conditioning, while simultaneously storing carbon dioxide for a relatively modest cost (Akbari et al., 1988). Cities have undertaken large-scale tree planting programs to improve air quality, lower summer temperatures, and beautify neighborhoods. In Los Angeles, a nonprofit group called TreePeople organized a successful effort to plant a million trees prior to the 1984 Olympic games. A new initiative announced by Mayor Bradley in October 1988 calls for planting five million trees and painting surfaces light colors to save 500 MW of peak power, or the equivalent of a large new coal plant (LBL, 1988).

Some States have also taken steps to help reduce emissions of CFCs. For example, Massachusetts recently fined a foam manufacturer for failing to recover CFCs, and obtained an agreement from the company that it will reduce emissions in the future (*New York Times*, August 25, 1988, p. A-21).

PRIVATE SECTOR EFFORTS

Because of the global nature of the greenhouse problem and the lack of direct economic incentive for solutions, much of the impetus for solutions will have to come from governments. Nevertheless, private corporations, non-governmental organizations, and individuals can make important contributions without waiting for government direction. Indeed, there are already several good examples of private initiatives that will contribute to reducing greenhouse gas emissions.

There have also been a number of important actions by private companies to reduce emissions of CFCs in advance of any government mandate. In September 1986--a year before the Montreal Protocol--the DuPont Company announced that they could produce chemical replacements for ozone-depleting CFCs within 5 years if governments provided proper regulatory incentives to support the new market. The substitutes either do not contain chlorine, the chemical that threatens the ozone layer, or they contain hydrogen, resulting in a much shorter and therefore less dangerous atmospheric lifetime. As evidence of the risk to the ozone layer mounted, other companies also announced support for efforts to reduce CFC emissions. The food packaging industry, for example, voluntarily agreed to substitute food packaging made with HCFC-22 rather than with CFC-12; HCFC-22 has an ozone-depletion and greenhouse potential roughly one-twentieth that of CFC-12, as discussed in Chapter III.

Since March 1988, when the NASA Ozone Trends Panel announced its conclusion that global ozone depletion has been detected, several major CFC producers and users have stated their support for an orderly phase-out of all production of CFCs by the turn of the century. Some companies have restricted sales to existing markets, stopped development work on new applications for regulated products, and committed not to increase production capacity nor sell technology to others.

It is often the private non-governmental organizations that are uniquely capable of promoting grassroots development and alleviating poverty (World Bank, 1984). The World Bank has supported the involvement of private companies in the design and implementation of projects, particularly projects on social forestry, agroforestry, and the environment. AID and the Peace Corps have given a high priority to involving private voluntary organizations in community forestry projects undertaken through the Food for Peace Program (Joyce and Burwell, 1985). The Tropical Forest Action Plan also includes strong support for involving private organizations.

Applied Energy Services (AES) of Arlington, Virginia, a private company involved in cogeneration projects, recently hired a non-profit organization, the International Institute for Environment and Development (IIED), to assist in identifying potential reforestation projects capable of providing a carbon sink equal to the emissions from a new 180 MW coal-fired plant in Connecticut. This approach reflects the offset concept discussed above. One problem in making this exchange on a voluntary basis was that the company had difficulty obtaining financing despite the small cost of the trees relative to the total project.[11]

Many of the strategies necessary to reduce greenhouse gas emissions require changes in technologies or policies that can only be accomplished by large corporations and governments. However, there are some important exceptions, particularly tree planting. Reviving the tradition of Arbor Day could provide a very effective symbol of individual responsibility for greenhouse gas emissions; one hectare of well-managed Douglas fir trees can absorb the average American's lifetime per capita emissions of CO_2 (about 400 tons, or 5 tons C/year x 80 years).[12] The cost of planting that many trees on a large scale is difficult to estimate, but $1500 is a reasonable approximation--a large but not impossible lifetime investment.[13]

---

[11] The program will cost the company $2 million for an endowment to finance a 10-year tree planting program by CARE, the Guatemalan forest service, and the Peace Corps to support 40,000 small farmers in planting 52 million trees in plantations and agroforestry systems. Over the 40-year life of the plant, 15 million tons of carbon will be fixed at a total cost of $14 million cash and contributed labor. AES is considering providing similar offsetting forestry projects for nine other plants. The costs are expected to be only about 0.1 cents per kWh because the projects will take place in developing countries and some labor will be contributed. CARE officials informally estimate that the project could be replicated perhaps 100 times given current institutional capability and land availability (WRI, 1988).

As these examples suggest, the government can help foster private initiatives. In some cases regulatory obstacles impede voluntary efforts and government can help remove them; in other cases the government may be able to help bring parties together and provide technical information or assistance. The important point is that government can help promote voluntary efforts to reduce greenhouse gas emissions.

COMPLEMENTARY STRATEGIES TO REDUCE GREENHOUSE GAS EMISSIONS

The policies described in this chapter are likely to be most effective when used in combination and, wherever possible, linked to the attainment of other national goals. Pricing and regulatory strategies are the most effective policies in the short term, however, the other policies reviewed in this section can complement and enhance pricing and regulatory approaches. In the long run, government-supported R&D, information programs, and other market-enhancing activities can make a significant contribution. Because government action to reduce greenhouse gas emissions will often be closely related to other national policies, programs must also be carefully crafted to meet several goals simultaneously (IEA, 1987).

Improving the efficiency of the U.S. economy is closely related to concerns about the country's economic competitiveness. While the U.S. has reduced its energy intensity a great deal, our principle economic competitors have done even better and can offer more efficient technologies in many areas. Per capita energy consumption in the U.S. remains more than double that of Europe or Japan; Japanese industry uses half as much energy per dollar of value added as industry in the U.S although spending about as much due to higher energy prices (Zimmerman and Reid, 1988; Flavin and Durning, 1988). Efficiency investments would make available billions of dollars in capital for other investments (Rosenfeld and Hafemeister, 1988). Oil imports are also a growing negative influence on the U.S. balance of trade, accounting for roughly a fourth of the merchandise trade deficit--more than any other single item (Chandler et al., 1988).

---

[12] Other species would require more land but with research it may be possible to do substantially better.

[13] A more detailed discussion of the feasibility of large-scale tree planting is provided in Chapter VII.

Policies for reducing greenhouse gas emissions may also complement efforts to address concerns raised by recent growth in oil imports and potential risks to U.S. energy security (U.S. DOE, 1987c). Oil imports have increased from 27 percent of U.S. supply in 1985 to about 37 percent in 1988, and current forecasts indicate imports could exceed 50 percent by the mid-1990s (U.S. DOE, 1987c). By comparison, imports accounted for 35 percent of supply before the 1973 embargo and 43 percent before the 1979 embargo.

As discussed in Chapter IV, oil consumption for transportation is one of the largest sources of U.S. greenhouse gas emissions, as well as a major contributor to projected increases in global emissions. Transportation also accounts for almost two-thirds of U.S. oil consumption. Further improvements in auto efficiency could therefore contribute to both policy objectives (Mackenzie, 1988).

Complementary strategies are very important in the building sector, where the effectiveness of pricing strategies is limited by extreme first-cost sensitivity and the stringency of regulation is likely to reflect considerable compromise. Studies show that selective financial incentives in combination withinformation and training programs can be highly effective in promoting innovation not covered by standards, creating incentives for early adoption of standards, and enhancing compliance with standards. The result can be performance that is substantially better than compliance with minimum standards would produce (Vine and Harris, 1988).

Complementary strategies can also work well to achieve the goal of reducing carbon emissions from automobiles. To achieve this goal, which is clearly consistent with efforts to promote higher average fuel economy, consumers must be able to evaluate the relative fuel efficiency of automobiles; Federal fuel efficiency tests, gas mileage guides, and other information programs promote this goal.[14] Manufacturers have rightfully noted that consumer interest in fuel efficiency has declined with lower gasoline prices; higher gasoline taxes, gas guzzler fees, or some other form of economic incentive is necessary to stimulate demand for efficiency.

Better management of solid wastes can reduce methane emissions. States with the most effective programs often combine some or all of the following policies: regulations on landfills, deposits on recyclable materials, tax incentives for recycling companies, and government procurement policies that promote purchase of recycled materials (Shea, 1988).

Research and development programs can assist on the supply side by accelerating the development and testing of new technologies. Procurement programs can provide an initial market and extensive testing for concepts prior to wider marketing. Minimum fuel economy standards fill a different role by providing clear targets and reducing market uncertainty, but regulations must be carefully structured to allow adequate time for adjustment, to avoid conflicts with other socially desirable features, and to preserve fair competition.

---

[14] The Department of Energy publishes *Gas Mileage Guides*, which list the fuel economy of all new car models; however, the number of guides distributed has been reduced from 10 million to 3 million annually.

There is some concern that other national policies for reducing automobile oil consumption and improving urban air quality may lead to increased carbon emissions--for example, if methanol is produced from coal in large quantities (as discussed in Chapter VII), particularly if vehicles using such fuels are permitted to be less efficient as provided in recent Federal legislation.

Federal and state governments have also been considering air pollution regulations to control problems other than global warming that could unintentionally exacerbate global warming. Most prominent of these areas is the ongoing debate over acid rain legislation. Acid rain is caused in part by sulfur dioxide and nitrogen oxide emissions from electric utility powerplants. Some of the methods to limit these emissions could result in greater CO_2 emissions. For example, the use of scrubbers to control sulfur dioxide emissions from coal-fired or oil-fired powerplants would increase CO_2 emissions because the additional fuel required to operate the scrubbers would produce additional CO_2 emissions. However, strategies that rely on natural gas or demand-side reductions would reduce carbon emissions (Centolella et. al., 1988). Thus, an important priority for acid rain mitigation strategies should be to consider the global warming impacts of alternative acid rain programs.

Just as strategies to reduce greenhouse emissions must be applied in combination in order to be maximally effective, so too must we work together at all levels of government, as well as in the private sector.

Many short-term actions to reduce greenhouse gas concentrations could be implemented today on the basis of existing legislative authority. Indeed, some policies directed toward this objective are already under consideration. For example, agencies could make greater use of the environmental impact statement process to consider the extent to which their major projects will contribute to or be effected by climate change. The President's Council on Environmental Quality has done an analysis of projects that might warrant discussion of climate change issues and may issue guidelines for other agencies. EPA, which is legally required to review draft impact statements, has used its authority in at least one instance to comment on the additional greenhouse gas emissions that might result from actions proposed by the Federal Energy Regulatory Commission.

Much more could be done to improve the federal government's energy management within existing legislative authority, beginning with much more disaggregated reporting of energy use by agencies. The laws creating the Federal Energy Management Program require an examination of opportunities for energy-saving alternatives in federal buildings. Such analysis is to be done on the basis of life-cycle costs, reflecting marginal fuel costs and a 7 percent real discount rate--terms intended to favor conservation, as compared with using average costs and a higher discount rate. (Energy Security Act, PL 96-294, Section 405). The Department of Energy proposed implementing regulations in 1980, but final regulations were never completed.

Other short-term possibilities follow from some of the recent and pending agency decisions discussed above, such as ongoing consideration of rules to promote demand-side bidding by the FERC and reconsideration of CAFE standards by the Department of Transportation.

IMPLICATIONS OF POLICY CHOICES AND TIMING

The potential cost of government action to reduce greenhouse gas emissions may be much less than it would appear if such action serves other important economic or environmental objectives. Most of the measures proposed to reduce emissions are already of substantial public interest, for example, policies that promote energy efficiency, reductions in use of CFCs, efforts to halt deforestation, and other desirable social policies--so that the threat of a global warming is often simply another reason to implement such policies. The incremental cost of taking actions to limit global warming today may therefore be modest.

best copy available

The technical feasibility of implementing various measures that have been proposed for limiting global warming has already been addressed in Chapter VII. However, since the threat of global warming has so far not been an important consideration in government policy-making, it is important to note the other benefits of these measures. For example, serious consideration is being given to eliminating emissions of CFCs because of their impact on the ozone layer. In addition, a substantial number of states are promoting investments in energy-efficient technology in order to reduce energy costs and to meet the need for new generating capacity. Also, Federal and state authorities are promoting waste reduction and recycling as alternatives to land disposal because of the high cost and environmental risks associated with traditional disposal methods. Finally, a large and growing international effort has been organized to slow tropical deforestation because of its impact on economic development and the quality of life in many developing countries.

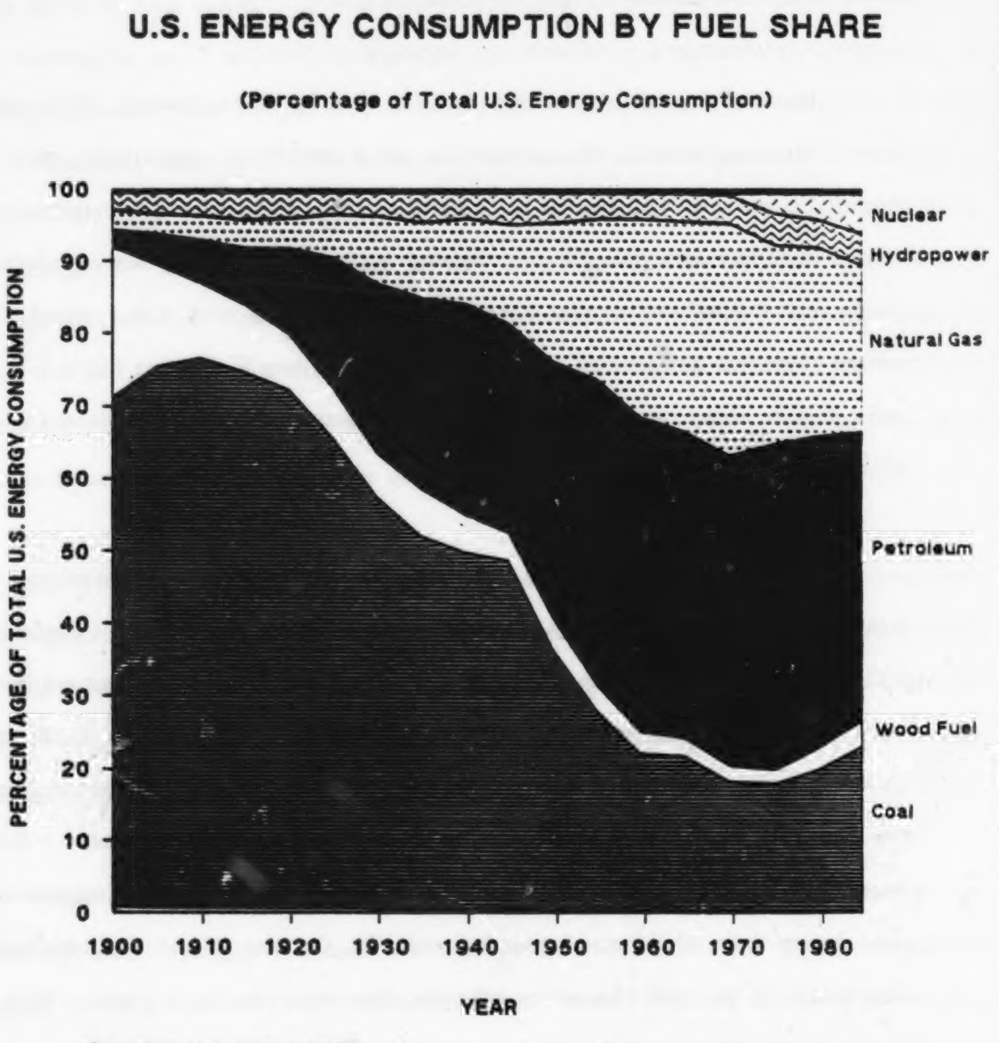
For several reasons, near-term action may be necessary if it is desired to stabilize greenhouse gas concentrations. For political and economic reasons, actions cannot be immediately implemented once it is agreed they are needed, and for reasons having to do with atmospheric chemistry, concentrations of greenhouse gases--and the attendant risks--will decline only gradually even after actions are implemented.

Policy development and implementation can be a lengthy process, particularly at the international level. Roughly a decade was required for the process that led to international agreement to reduce emissions of CFCs embodied in the Montreal Protocol, and it will take another decade to implement the agreed-upon reductions. An agreement to reduce emissions of greenhouse gases associated with the use of fossil fuels and with deforestation could take much longer to achieve: the activities responsible for CO_2 emissions are more economically valuable, the distribution of emissions is greater, the responsible countries have diverse economies and less shared interests, and the difficulty of implementing alternatives may be greater.

Implementing new technologies can also often be time-consuming. Most emissions result from fundamental activities that support the global economy (transportation, space conditioning, industrial production, land clearing, etc.); therefore, rapid introduction of new technologies for some uses could be very disruptive. Once a technology is cost-effective, it may take years before it achieves a large market share, and decades more for the existing capital stock to be replaced. The historical pattern of gradual displacement of old energy sources by new is shown in Figure 8-7. Government policy may be able to significantly accelerate this transition, although it is debatable whether such efforts have been very successful in the past.

New end-use technology with greater efficiency can replace existing technologies more quickly: it takes 5-10 years to develop new automobile models, and the existing fleet is largely replaced over 8-12 years; major home appliances and space heating and conditioning systems are in use for 10-20 years, and industrial equipment, for 20-40 years. Buildings may be used for 40-100 years or more, however, and the reduction in energy requirements that can be achieved (per unit) as a result of remodeling is more limited than what can be achieved in newly-constructed buildings. Thus, depending on the sector, it traditionally takes roughly 20-50 years to substantially alter the technological base of industrial societies, and thus the cost of reducing emissions could rise dramatically as the time allowed for achieving these reductions is decreased. While the rate of change can be higher in rapidly developing countries, once the industrial infrastructure is built, it will normally be many years before it is replaced. This process will be naturally accelerated if new technologies become sufficiently attractive, and government policies can encourage more rapid retirement of existing buildings and equipment. Nevertheless, such efforts are likely to be more expensive and technically difficult.

FIGURE 8-7



Source: U.S. DOE, 1987a.

Once greenhouse gases have entered the atmosphere, they continue to affect climate for decades. Even if all anthropogenic emissions of carbon dioxide could be suddenly eliminated, it may take more than a century for the oceans to absorb enough carbon to reduce the atmospheric concentration of CO_2 even half way toward its preindustrial value (see discussion in Chapter II). With continued emissions, the time required to reduce excess concentrations by the same percentage increases further. For CFCs and N_2O, it would be more than 50 years before their excess concentrations declined by half even if all anthropogenic emissions were eliminated. Only methane responds relatively quickly--the excess concentration would fall by 50 percent in less than a decade after anthropogenic emissions were eliminated (Figure 8-8).

The climate response also lags behind the radiative forcing imposed by changes in atmospheric composition (Chapter III). Due to the heat capacity of the ocean, the global average temperature will rise more slowly than if climate were continuously in equilibrium with the changing composition of the atmosphere. The climate will also cool more slowly if trace-gas trends are reversed. Consequently, any strategy that involves responding to climate impacts is very risky: Once climate change occurs even draconian measures would not reverse the process for decades.

SENSITIVITY TESTS OF THE EFFECT OF ALTERNATIVE POLICIES ON GREENHOUSE GAS EMISSIONS: RISK TRADE-OFFS

A series of sensitivity tests were run using the EPA's Atmospheric Stabilization Framework to test the relative effect of a range of policies that might increase or moderate greenhouse gas emissions. These tests involved changing key parameter values in the Rapidly Changing World No Response scenario (RCW) and the Rapidly Changing World with Stabilizing Policy scenario (RCWP) to represent more aggressive government intervention. The following section summarizes the results of those sensitivity tests and concludes with some suggestions concerning possible future targets for policy intervention. (For a detailed description of the assumptions and outcomes incorporated into

FIGURE 8-8

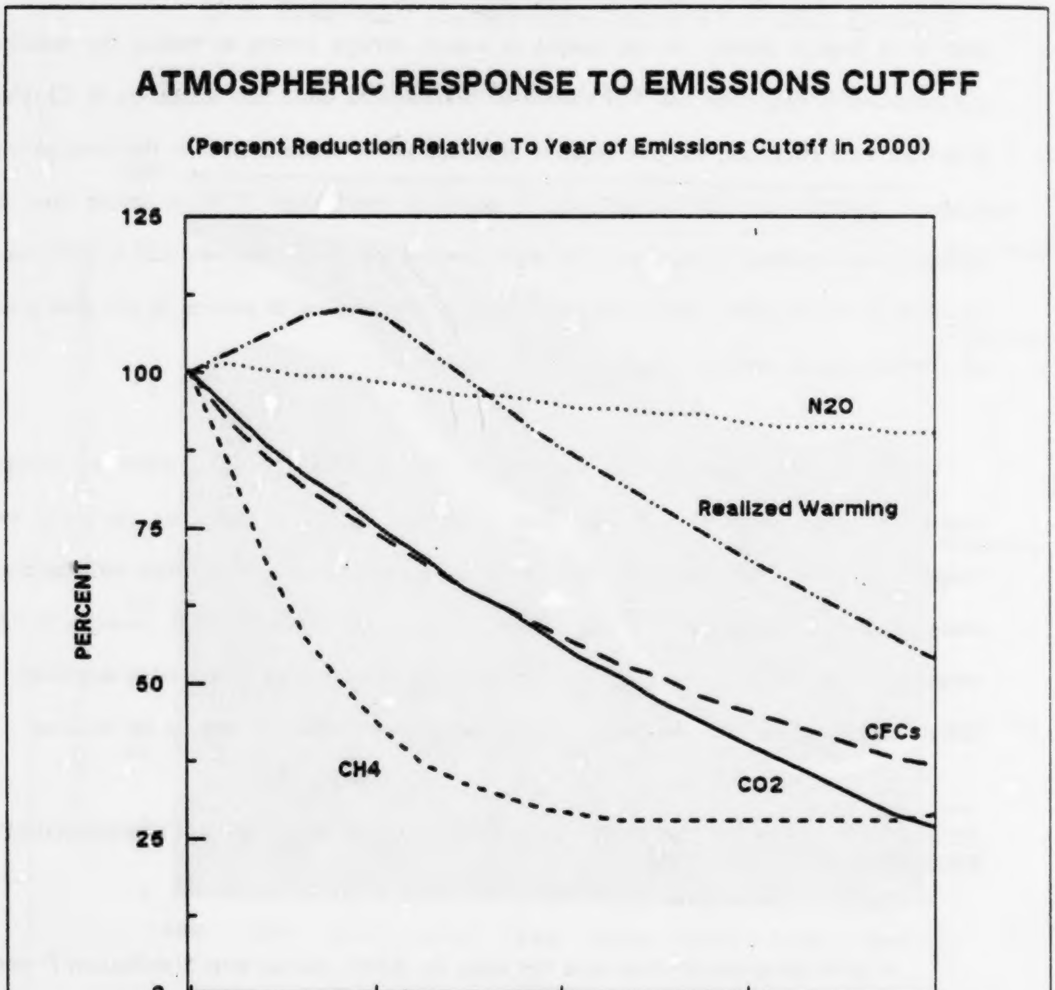


Figure 8-8. Change in atmospheric concentration and temperature following a cutoff in anthropogenic emissions of greenhouse gases. 100% is defined as the year 2000 concentration or temperature and 0% as the preindustrial concentration or temperature. Total methane emissions are reduced to 380 Tg per year, which may represent only a 50% reduction in anthropogenic emissions.

the RCW and the RCWP scenarios, the reader is referred to Chapter V and Appendix B of this report.)

To measure the impact of a range of specific policy goals in the RCW scenario, two sets of sensitivity tests were developed. In each case, the effects of the policy alternatives were first evaluated individually and then in combination to measure the impact of implementing all the identified measures simultaneously. The results were evaluated in terms of the degree to which the projected global warming was amplified or reduced relative to the reference scenarios.

Policies That Increase Greenhouse Gas Emissions

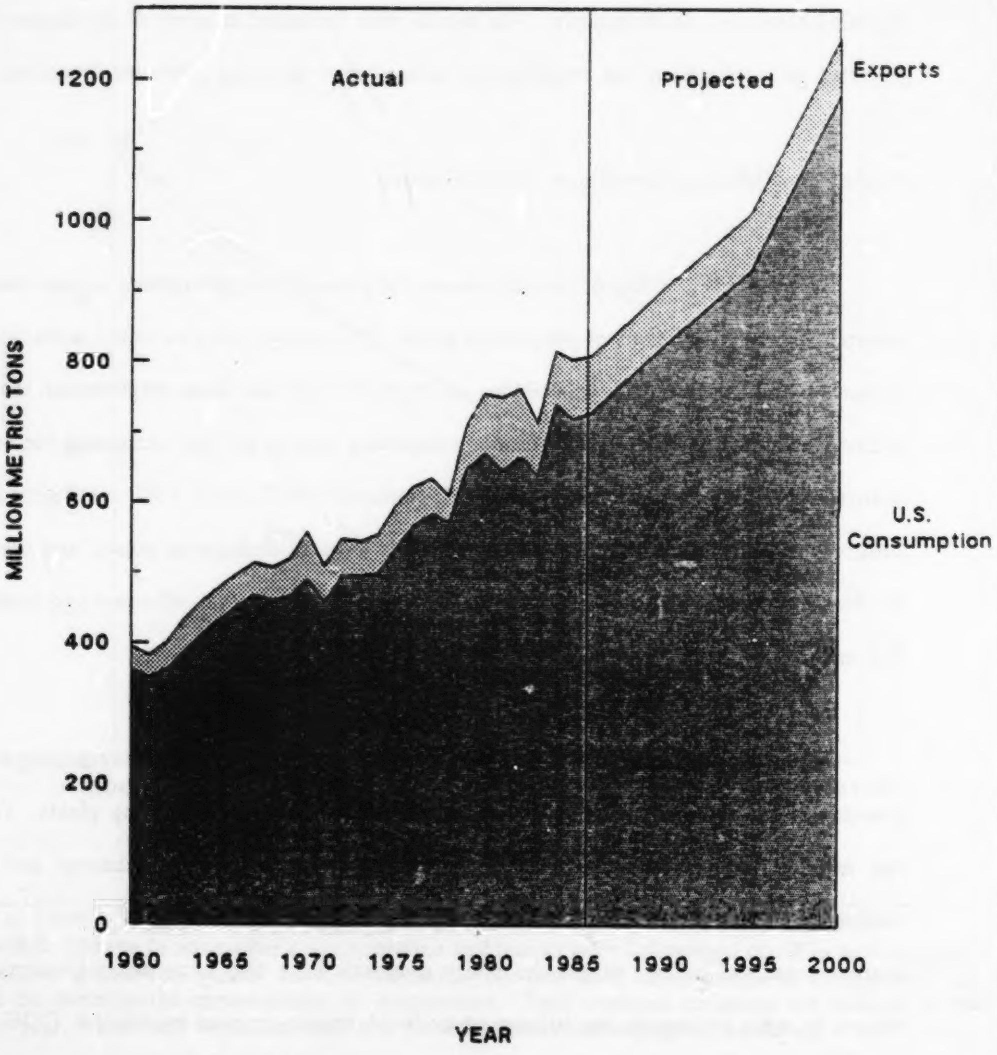
Several recent policy proposals indicate the potential for government actions that will or may promote increased emissions of greenhouse gases. U.S. energy policy currently seeks to increase coal production and use to reduce dependence on imported fuels and boost employment; the Department of Energy has made numerous suggestions concerning various policies to increase the role of coal in relative and absolute terms (U.S. DOE, 1987; National Coal Council, 1987; see Figure 8-9). Recent initiatives in utility regulation and alternative fuels have an ambiguous impact and the Department of Transportation has also decided not to increase automobile fuel efficiency requirements beyond 26.5 mpg.

Improving the efficiency of coal combustion in so-called "clean coal" technologies may reduce greenhouse gas emissions relative to the current generation of coal-burning plants. Over the long run, however, more efficient coal-burning technologies may increase greenhouse gas emissions by making coal economically attractive relative to other fuels. (This proposition is tested in the modeling analysis presented below.) Numerous policy proposals have also been made to increase U.S. coal exports in order to improve the balance of trade. A recent proposal by the U.S. DOE coal advisory

FIGURE 8-9

ACTUAL AND PROJECTED U.S. COAL PRODUCTION

(Million Metric Tons)



Source: U.S. DOE, 1987a.

committee would link exports of clean-coal technology to an agreement to purchase U.S. coal policy that might slow the adoption of more efficient technology for burning less expensive domestic coal in some developing countries like China (National Coal Council, 1987).

The need to more carefully consider the potential impact of government decisions on greenhouse warming is evident from analyses of two recent policies with ambiguous impact on greenhouse warming. The Methanol and Alternative Fuels Promotion Act enacted this year creates incentives for auto manufacturers to produce vehicles powered by methanol, ethanol, and substitutes for gasoline. This program was adopted to lessen dependence on imported oil and improve urban air quality. However, during Congressional debates concern was expressed that if methanol were produced in large quantities from coal, the result would be a significant increase in greenhouse gas emissions. Congress therefore included provision for study of this relationship. (The potential effect of accelerated synfuels development is presented below.)

Another example of a policy with ambiguous but potentially significant effects on greenhouse gas emissions is rule changes proposed by the Federal Energy Regulatory Commission (FERC) to facilitate non-utility power production. The draft environmental impact statement (DEIS) on these rules concluded that coal-fired technologies have so far played a limited role in the development of independent power projects relative to resource recovery, hydro power, and natural gas. As a result of the FERC proposals, coal could assume a much larger role in the future because of proposed elimination of requirements for cogeneration incompatible with the most economic coal technologies and because larger firms with the resources necessary to undertake large-scale projects that increase the attractiveness of coal technologies may find the power market more attractive. However, alternative assumptions imply natural gas will grow much more than coal (FERC, 1988b).

A set of tests applied to the RCW case measures the effect of policy choices that cause future emissions to grow. In this "Accelerated Emissions" case, eight key parameters in the model, representing domestic and international policies that increase emissions, were varied. These parameters were chosen as proxies for currently-proposed policies (e.g., accelerated development of synfuels) or as possible consequences of government inaction or failure (e.g., high CFCs and deforestation).

The tested policy alternatives included the following:

- A High CFC Case, which assumed a low level of participation in and compliance with the Montreal Protocol.
- A Cheap Coal Case, which assumed that advances in the technology of coal extraction and transport rapidly reduce the market price of coal at the burner tip. In the RCW scenario, coal supply productivity was assumed to improve at a rate of approximately 0.5 percent per year. In this case, it is assumed to improve at a rate of 1 percent per year.
- A Cheap Synfuels Case, which assumed that the price of synthetic oil and gas could be reduced by 50 percent and commercialization rapidly accelerated relative to the RCW case. This case assumes that the minimal production price for synfuels can be achieved in 20 years rather than the 30 years assumed in the RCW case.
- A High Oil Price Case, which assumed that OPEC (or some other political entity) could control production levels and thus raise the border price of oil and gas. To simulate this effect, oil and gas resources were shifted to higher points on the regional supply curves. In addition, extraction costs for oil in each resource grade were increased relative to the assumptions in the RCW case.

- A Slow Improvement Case, which assumed that technical gains in the engineering efficiency of energy use occurred only half as rapidly as had been assumed in the RCW case. In the RCW case, it was assumed that efficiency improved at rates of approximately 1-2 percent per year. In the Slow Improvement case, the assumed rates were reduced to only 0.5-1.0 percent per year.
- A Rapid Deforestation Case, which assumed that rates of deforestation increased at a rate equal to the rate of growth in population.
- A High-Cost Solar Case, which assumed that solar energy was so expensive that its price precluded the possibility of making any significant contribution to global energy supply.
- A High-Cost Nuclear Case, which assumed that the cost of electricity from fission electric systems became so high that their contribution to global energy supply was permanently limited. In this case, an environmental tax of $20/GJ in 1975$ (i.e., $40/GJ in 1985$) was imposed on the price of electricity supplied by nuclear powerplants.
- A Combination Case, in which all of these policy strategies were combined in one scenario.

Figure 8-10 summarizes the results of these sensitivity tests as compared with the RCW case. The results are illustrated in terms of the incremental effect of each policy strategy on the warming commitment in the RCW scenario in 2050 and 2100. Figure 8-10 indicates that the measures that amplify the warming to the greatest extent are those that (1) reduce the rate of efficiency improvement (Case 5), (2) reduce the cost of synfuels (Case 3), and (3) increase the assumed rate of growth in CFC production and use (Case 1).

FIGURE 8-10

ACCELERATED EMISSIONS CASES: PERCENT INCREASE IN EQUILIBRIUM WARMING COMMITMENT

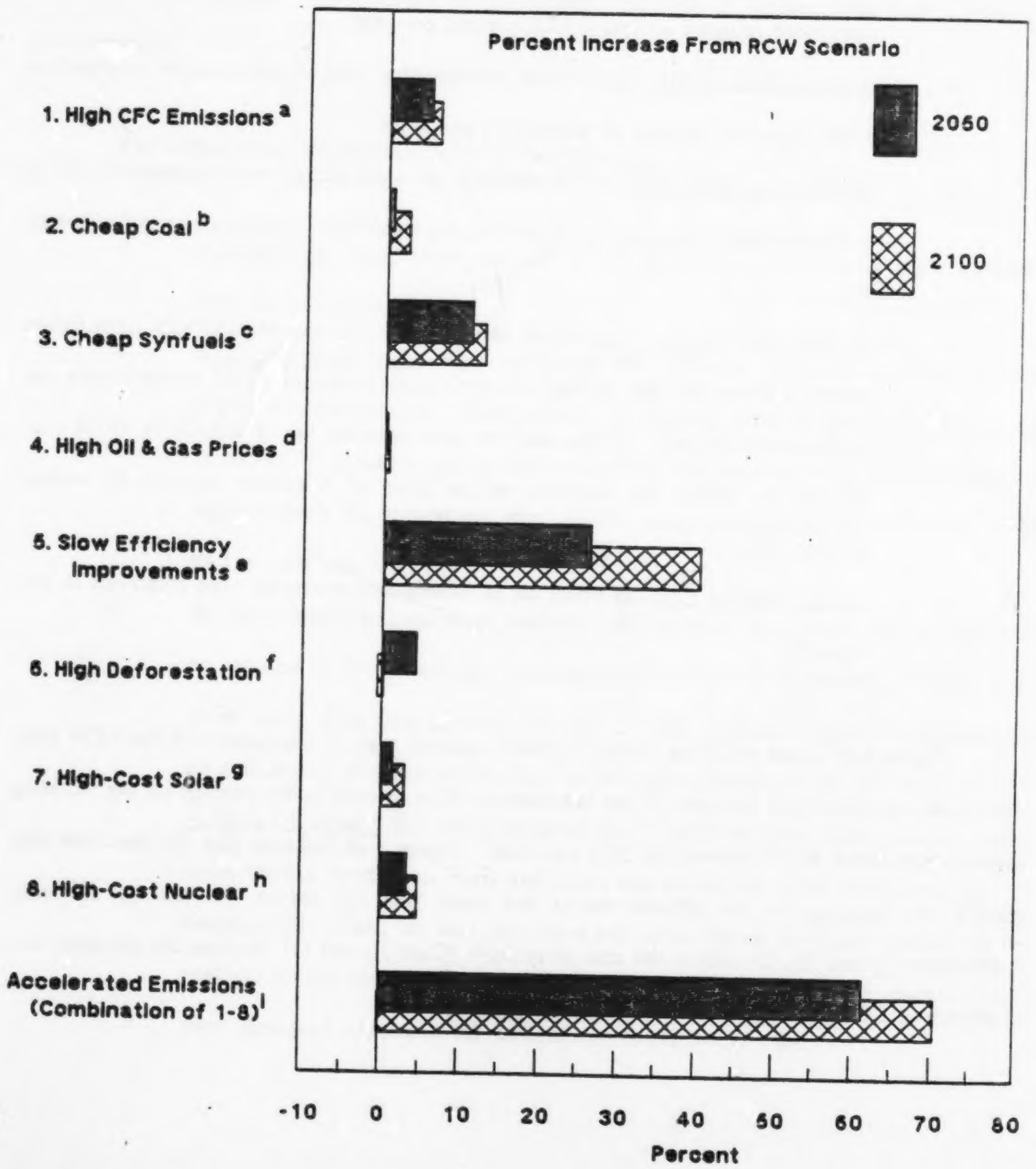


FIGURE 8-10 -- NOTES

Impact Of Accelerated Emissions Policies On Global Warming

[a] Assumes a low level of participation in and compliance with the Montreal Protocol. The assumptions used in this case are similar to those used in the "Low Case" analysis described in the EPA's Regulatory Impact Assessment report.

[b] Assumes that advances in the technology of coal extraction and transport rapidly reduce the market price of coal at the burner tip. In the RCW scenario, the economic efficiency of coal supply is assumed to improve at a rate of approximately 0.5% per year. In this case, it is assumed to improve at a rate of 1% per year.

[c] Assumes that the price of synthetic oil and gas could be reduced by 50% and commercialization rapidly accelerated relative to the RCW case. This case assumes that the minimal production price for synfuels can be achieved in 20 years rather than the 30 years assumed in the RCW case.

[d] Assumes that OPEC (or some other political entity) could control production levels and thus raise the border price of oil and gas. To simulate this effect, oil and gas resources were shifted to higher points on the regional supply curves. In addition, extraction costs for oil in each resource grade were increased relative to the assumptions in the RCW case.

[e] Assumes that technical gains in the engineering efficiency of energy use occurs only half as rapidly as assumed in the RCW case. In the RCW case it is assumed that efficiency improves at rates of approximately 1-2% per year. In the Slow Improvement case the assumed rates were reduced to only 0.5-1.0% per year. The lower rate of improvement is similar to the assumptions in recent projections for the Department of Energy's National Energy Policy Plan.

[f] Assumes annual deforestation increases at a rate equal to the rate of growth in population.

[g] Assumes that solar energy remains so expensive that its price precludes the possibility of making any significant contribution to global energy supply.

[h] Assumes that the cost of electricity from fission electric systems becomes so high that their contribution to global energy supply is permanently limited. In this case, an environmental tax of about $40 (1985$) per gigajoule (GJ) on the price of electricity supplied by nuclear powerplants was phased in by 2050.

[i] All of the above assumptions were combined in one scenario. The result is not equal to the sum of the warming in the RCW and the eight individual cases because of interactions among the assumptions.

Policies Designed to Reduce Greenhouse Gas Emissions

The second set of tests, called the Rapid Reduction scenario, examines the effect of measures that might be imposed to supplement those already analyzed in the RCWP scenario. The assumptions made in this case imply more aggressive response to the risks associated with rapid climate change and the near-term adoption of strategies that rapidly reduce the rate of emissions growth. To parallel the accelerated emissions case, eight separate policy strategies were also tested individually and in combination in this exercise by varying key parameters in the model.

The tested policy alternatives included the following:

- A Production Fee Case, in which fees are imposed on the production of fossil fuels in proportion to the CO_2 emission potential. In this case, fees of $8.50/GJ were imposed on unconventional oil production, $5.70/GJ on coal, $2.30/GJ on oil, and $1.10/GJ on natural gas. These fee levels are specified in 1985$ and are phased in over the period between 1985 and 2050.[15]

---

[15] The revenue implications of these fees (in billions of U.S. dollars) are as follows:

RCWP

Year	US	Global
2000	$30	$134
2025	$46	$338
	Additional Production Fee	
2000	$54	$293
2025	$73	$605
	Consumption Fee	
2000	$59	$255
2025	$70	$507

- A Consumption Fee Case, in which a percentage fee, proportional to the carbon content of the fuel, was levied on fuel use. Consumption fees were also imposed in the RCWP case. In this sensitivity case, the fee on coal consumption was increased from 28 percent of the price to 40 percent; the fee on oil use was increased from 20 percent to 30 percent; the fee on natural gas use was increased from 13 percent to 20 percent; the fee on electricity use was increased from 0 to 5 percent. These fees were phased in and fully applied by 2025.
- A High-mpg Car Case, in which global fleet-average auto efficiencies reach 65 mpg in 2025 and 100 mpg in 2050.
- A High Efficiency Buildings Case, in which the rate of technical efficiency improvement in the residential and commercial sectors improves substantially beyond that assumed in the RCWP case. In this case, the rate of efficiency improvement in the residential and commercial sectors is increased so that a net gain in efficiency of 50 percent relative to the RCWP case is achieved in all regions.
- A High Efficiency Power Case, in which, by 2050, average powerplant conversion efficiency improves by 50 percent relative to the RCWP case. In this scenario, the design efficiencies of all types of generating plants improve rapidly. For example, by 2025, oil-fired generating stations achieve an average conversion efficiency roughly equivalent to that achieved by combined-cycle units today.
- A High Biomass Case, in which the availability of commercial biomass was doubled relative to the assumptions in the RCWP case. In this case, biomass availability was assumed to follow the trajectory outlined in the U.S. DOE Biofuels Program. Conversion costs were assumed to fall by half relative to the assumptions in the RCWP scenario.
- A No Coal Case, in which environmental fees of approximately $20/GJ in 1985$ drove coal out of the bulk power markets by 2050;

- A Rapid Reforestation Case, in which deforestation is halted by 2000 and the biota become a net sink for CO_2 at a rate of about 1 Pg C per year by 2025, about twice the level of carbon storage assumed in the RCWP case.
- A Do It All Case, in which all of the above measures are implemented simultaneously. The impact is much less than the sum of the individual components because many of the measures are not additive.

Figure 8-11 summarizes the results of the second set of sensitivity tests as compared with the RCWP case. The results are illustrated in terms of the effect of each policy strategy in reducing the warming commitment from the RCWP scenario in 2050 and 2100 relative to the RCW scenario (for consistency with the Accelerated Emissions case). Figure 8-11 indicates that the measures that reduce the warming to the greatest extent are those that (1) drive coal out of the power markets (Case 7), (2) impose stiff fees on the production of fossil fuels (Case 1), and (3) increase the assumed level of biomass availability (Case 6).

Conclusions From the Sensitivity Tests

This analysis demonstrates that policy choices can significantly affect the timing and magnitude of future global warming. Comparing the results in Figures 8-10 and 8-11 suggests, however, that the effects of policy choices that increase the rate of growth in greenhouse gas emissions could be much larger than the effects of policies that accelerate reductions in future emissions rates. In other words, it may be easier for government policy to worsen the problem than to ameliorate it. If the policies evaluated here are representative of the range of relevant choices, policies that increase emissions may make the situation much worse than current trends suggest, and may have large effects very quickly.

FIGURE 8-11

RAPID REDUCTION STRATEGIES: ADDITIONAL DECREASE IN EQUILIBRIUM WARMING COMMITMENT

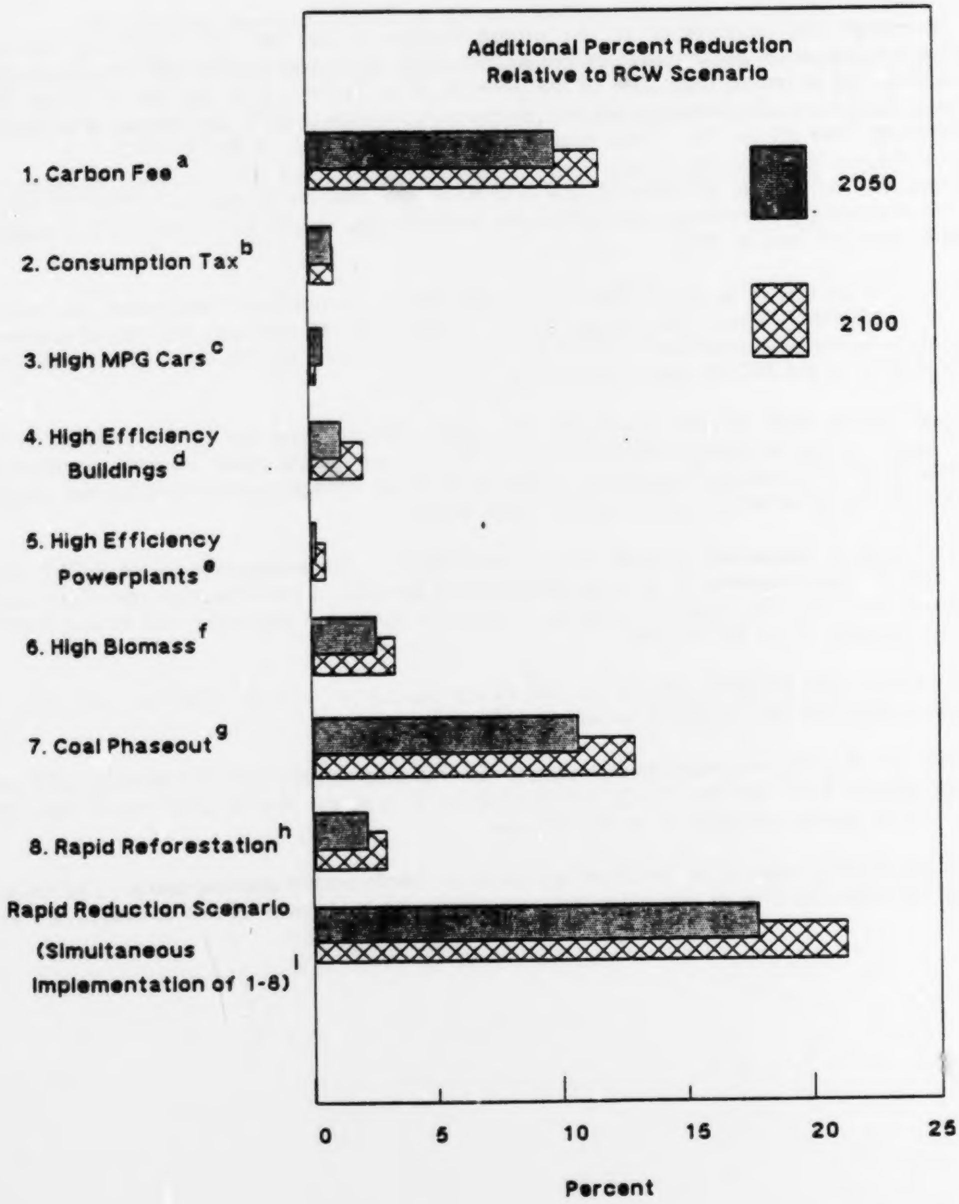


FIGURE 8-11 -- NOTES

Impact Of Rapid Reduction Policies On Global Warming

[a] High carbon emissions fees are imposed on the production of fossil fuels in proportion to the CO_2 emissions potential. In this case, fees of $8.50/GJ were imposed on unconventional oil production, $5.70/GJ on coal, $2.30/GJ on oil, and $1.10/GJ on natural gas. These fee levels are specified in 1985$ and are phased in over the period between 1985 and 2050.

[b] A percentage fee, proportional to the carbon content of the fuel, was levied on fuel use. Consumption fees were also imposed in the RCWP case. In this sensitivity case, the fee on coal consumption was increased from 28% of the price to 40%; the fee on oil use was increased from 20% to 30%; the fee on natural gas use was increased from 13% to 20%; the fee on electricity use was increased from 0% to 5%. These fees were phased in and fully applied by 2025.

[c] Assumes that the average efficiency of new cars in the U.S. reaches 50 mpg (4.7 liters/100 km) in 2000 and that global fleet-average auto efficiencies reach 65 mpg in 2025 (3.6 liters/100 km) and 100 mpg (2.4 liters/100 km) in 2050.

[d] Assumes that the rate of technical efficiency improvement in the residential and commercial sectors improves substantially beyond that assumed in the RCWP case. In this case, the rate of efficiency improvement in the residential and commercial sectors is increased so that a net gain in efficiency of 50% relative to the RCWP case is achieved in all regions.

[e] Assumes that, by 2050, average powerplant conversion efficiency improves by 50% relative to the RCWP case. In this the design efficiencies of all types of generating plants improve significantly. For example, by 2025, oil-fired generating stations achieve an average conversion efficiency roughly equivalent to that achieved by combined-cycle units today.

[f] The availability of commercial biomass was doubled relative to the assumptions in the RCWP case. In this case the rate of increase in biomass productivity is assumed to be at the high end of the range suggested by the U.S. DOE Biofuels Program. Conversion costs were assumed to fall by half relative to the assumptions in the RCWP case.

[g] Environmental fees of about $20/GJ (in 1985$) are phased in by 2050. This has the effect of gradually making coal uncompetitive in utility markets.

[h] A rapid rate of global reforestation is assumed. In this case deforestation is halted by 2000 and the biota become a net sink for CO_2 at a rate of about 1 Pg C per year by 2025, about twice the level of carbon storage assumed in the RCWP case.

[i] Impact on warming when all of the above measures are implemented simultaneously. The impact is much less than the sum of the individual components because many of the measures are not additive.

Of the options available to slow the rate of emissions growth, the most promising near-term strategies are measures to increase the efficiency of energy use. As noted earlier, these measures are improving rapidly and provide other substantial economic, social, and environmental benefits.

The warming estimates for all of the combination scenarios considered in this report are summarized in Table 8-8. Only the most aggressive policy case lowers realized warming below a tenth of a degree celsius per decade. Some experts have suggested this rate of change represents a maximum consistent with acceptable adaptation for many species of plants and animals (Woodwell, 1987).

TABLE 8-8

Scenario Results For Realized And Equilibrium Warming

Realized Warming - 2°C Sensitivity	1985	2000	2025	2050	2075	2100
Accelerated Emissions	0.5	0.7	1.5	2.8	4.5	6.3
RCW	0.5	0.7	1.2	1.9	2.7	3.6
SCW	0.5	0.7	1.1	1.6	2.0	2.5
RCWP	0.5	0.6	0.9	1.1	1.3	1.4
SCWP	0.5	0.6	0.9	1.0	1.2	1.2
Rapid Reduction	0.5	0.6	0.8	0.8	0.8	0.7

Realized Warming - 4°C Sensitivity	1985	2000	2025	2050	2075	2100
Accelerated Emissions	0.5	1.0	2.1	4.1	6.8	9.6
RCW	0.5	0.9	1.7	2.8	4.1	5.6
SCW	0.5	0.9	1.7	2.5	3.2	4.0
RCWP	0.5	0.9	1.4	1.8	2.1	2.3
SCWP	0.5	0.9	1.3	1.7	1.9	2.0
Rapid Reduction	0.5	0.9	1.3	1.4	1.3	1.2

Equilibrium Warming Commitment - 2°C Sensitivity	1985	2000	2025	2050	2075	2100
Accelerated Emissions	0.7	1.1	2.4	4.3	6.4	8.3
RCW	0.7	1.1	1.7	2.7	3.8	4.8
SCW	0.7	1.0	1.6	2.2	2.7	3.1
RCWP	0.7	1.0	1.3	1.5	1.6	1.7
SCWP	0.7	1.0	1.2	1.3	1.4	1.4
Rapid Reduction	0.7	1.0	1.1	1.0	.9	.7

Equilibrium Warming Commitment - 4°C Sensitivity	1985	2000	2025	2050	2075	2100
Accelerated Emissions	1.5	2.2	4.7	8.7	12.4	16.5
RCW	1.5	2.1	3.5	5.4	7.5	9.6
SCW	1.5	2.1	3.3	4.5	5.4	6.3
RCWP	1.5	2.0	2.5	2.9	3.2	3.3
SCWP	1.5	1.9	2.4	2.7	2.8	2.8
Rapid Reduction	1.5	1.9	2.1	2.0	1.7	1.3

REFERENCES

ABA (American Bar Association). 1980. *The Need for Power and the Choice of Technologies: State Decisions on Electric Power Facilities*. ABA Special Committee on Energy Law, Washington, D.C.

ACEEE (American Council for an Energy Efficiency Economy). 1988. *Proceedings of the 1988 ACEEE Summer Study on Energy Efficiency in Buildings* (11 volumes).

Akbari et al. 1988. The Impact of Summer Heat Islands on Cooling Energy Consumption and CO_2 Emissions. In *National and Regional Programs: Proceedings of the 1988 ACEEE Summer Study on Energy Efficiency in Buildings*.

Alliance to Save Energy. 1987. *Industrial Decision-Making Interviews: Findings and Recommendations*. Paper for Michigan Electricity Options Study.

Aronson, E., and S. Yates. 1985. Social Psychological Aspects of Energy Conservation. In Hafemeister, D., H. Kelly, B. Levi, eds., *Energy Sources: Conservation and Renewables*.

Berman, E., M. Cooper, and H. Geller. 1987. *A Compendium of Utility-Sponsored Energy Efficiency Rebate Programs* (EPRI EM-5579).

Bleviss, D. 1988. *The New Oil Crisis and Fuel Economy Technologies: Preparing the Light Transportation Industry for the 1990s*. Quorum, New York.

Carlson, D. 1988a. *Low-Cost Power from Thin-Film Photovoltaics*. Solarex, Newtown, PA.

Carlson, E. 1988b. *Florida Readies Broad Assault on Garbage*. Wall Street Journal, July 20, 1988, p. 25,50

Cavanaugh, R. 1986. Least-Cost Planning Imperatives for Electric Utilities and Their Regulators. *Harvard Environmental Law Review*. 10:299-344.

Cavanaugh, R., and E. Hirst. 1987. The Nation's Conservation Capital. *Amicus Journal* (Summer): 38-42.

Cavanaugh, R. 1988. (journal title?) *Yale Journal on Regulation* 5:331-366.

Centolella, P., F. Pultz, and E. Miller. 1988. Policy Implications of Relying Energy Conservation as an Acid Rain Control Strategy. In *National and Regional Conservation Programs: Proceedings of the 1988 ACEEE Summer Study on Energy Efficiency in Buildings*. ACEEE, Washington, D.C.

Chandler, W., H. Geller, and M. Ledbetter. 1988. *Energy Efficiency: A New Agenda*. ACEEE, Washington, D.C.

Claussen, E . 1988. Moving Forward Together. *Environmental Forum* 5(3): 14-16.

Cogan, D. 1988. *Stones in a Glass House: CFCs and Ozone Depletion*. Investor Responsibility Research Center, Washington, D.C.

Cole, J., and J. Rizutto. 1988. Residential Applications of Real Time Pricing. In ACEEE, *Utility and Private Sector Conservation Programs: Proceedings of the 1988 ACEEE Summer Study*. Washington, D.C.

Crandall, R., H. Gruenspecht, T. Keeler, and L. Lave. 1986. *Regulating the Automobile*. Brookings, Washington, D.C.

Dudek, D. 1988. Testimony before the Senate Committee on Energy and Natural Resources, September 19, 1988. Environmental Defense Fund, New York.

EEC (Commission of the European Communities), 1988. *The Main Findings of the Commission's Review of Member States' Energy Policies, The 1995 Community Energy Objectives*, COM(88) 174, Brussels.

FAO, WRI, World Bank, and UNDP (Food and Agricultural Organization of the United Nations, World Resources Institute, and U.N. Development Programme). 1987. *The Tropical Forestry Action Plan*.

FAO, WRI, World Bank, and UNDP (Food and Agricultural Organization of the United Nations, World Resources Institute, and U.N. Development Programme). 1987. *The Tropical Forestry Action Plan: Investment Priorities and Policy Reforms for Sustainable Forest Land Use*. Keynote paper prepared for the Bellagio Strategy Meeting on Tropical Forests. July 1-2, 1987.

FERC (Federal Energy Regulatory Commission). 1988a. Proposed Regulations Governing Bidding Programs (RM88-5-000), March 16, FERC, Washington, D.C.

FERC (Federal Energy Regulatory Commission). 1988b. Proposed Regulations Governing Independent Power Producers (RM88-4-000), March 16. FERC, Washington, D.C.

FERC (Federal Energy Regulatory Commission). 1988c. The Qualifying Facilities Report, (January 1). FERC, Washington, D.C.

Federal Register. August 12, 1988.

Flavin, C. 1988. Creating a Sustainable Energy Future. In Starke, L., ed., *State of the World 1988*. New York: W.W. Norton 22-40.

Forster, M. 1986. Two Cheers for the Agreement. *Environmental Policy and Law* 16(5): 142-143.

Geller, H. 1986a. Energy-Efficient Appliances; Performance Issues and Policy Options. *Technology and Society Magazine* March.

Geller, H. 1986b. Energy and Economic Savings from National Appliance Efficiency Standards. ACEEE, Washington, D.C.

Geller, H. 1988. Recent Growth in U.S. Energy Demand: A Preliminary Examination. ACEEE, Washington, D.C.

Goldemberg, J., T. Johansson, A. Reddy, and R. Williams. 1987. *Energy for Development*. World Resources Institute, Washington.

Goldemberg, J., T. Johannson, A. Reddy, and R. Williams, 1988. *Energy for a Sustainable World*. Wiley Eastern Limited, New Delhi, India.

Harris, L., and A. Kearney. 1988. Case Study of the North Carolina Alternative Energy Corporation. In *National and Regional Conservation Programs: Proceedings of the 1988 ACEEE Summer Study on Energy Efficiency in Buildings*. ACEEE, Washington, D.C.

Hirst, E., J. Clinton, H. Geller, and W. Kroner, 1986. *Energy Efficiency in Buildings: Progress and Promise.*

IEA (International Energy Agency). 1987. *Energy Conservation in IEA Countries*. OECD/IEA, Paris, 259 pp.

IIED and WRI (International Institute for Environment and Development and World Resources Institute). 1987. *World Resources 1987*. Basic Books, Inc., New York, 369pp.

Kahn, E. 1988. *Electricity Utility Planning and Regulation*. ACEEE, Washington, D.C.

Kempton, W., and M. Neiman, eds. 1987. *Energy Efficiency: Perspectives on Individual Behavior.* ACEEE, Washington, D.C.

Kerwin, J., and S. Jolin. 1988. Hybrids: New Generation of ESCOs? In ACEEE, *Community and Local Conservation Programs: Proceedings of the 1988 ACEEE Summer Study*. Washington, D.C.

Komor, P., and R. Katzev. 1988. Policies for Encouraging Energy Conservation in Small Commercial Buildings. In *Proceedings from the International Symposium: Energy Options for the Year 2000* (Volume 1). University of Delaware.

Krause, F. 1988. *Analysis of Michigan's Demand-Side Electricity Resources in the Residential Sector.* (LBL #2305). Berkeley, CA: Lawrence Berkeley Laboratory.

Lovins, A., and M. Shepard. 1988. Implementation Paper #1: Financial Electric End-Use Efficiency. Rocky Mountain Institute. Old Snowmass, Colorado.

Machado, S., and R. Piltz. 1988. *Reducing the Rate of Global Warming: The State's Role*. Renew America, Washington, D.C.

MacKenzie, J., 1988. *Breathing Easier: Taking Action on Climate Change, Air Pollution, and Energy Insecurity.* World Resources Institute, Washington, D.C.

Miller, A., I. Mintzer, and S. Hoagland. 1985. *Growing Power: Bioenergy for Development and Industry.* World Resources Institute, Washington, D.C.

Moskovitz, D. 1988. Will Least-Cost Planning Work Without Significant Utility Reform? Paper presented to the Least-Cost Planning Seminar of the National Association of Regulatory Utility Commissioners, Aspen, Colorado, April 12, 1988 (revised June 10, 1988).

McNutt, B., and P. Patterson, 1986. *Cafe Standards - Is a Change in Form Needed?* Paper presented at the Society for Automotive Engineers, September 22-25, 1986, Dearborn, Michigan.

National Coal Council. 1987. *Improving International Competitiveness of U.S. Coal and Coal Technologies*. National Coal Council, Washington, D.C.

Nivola, P. 1986. *The Politics of Conservation*. Washington, D.C.: Brookings Institution.

Novick, S., ed. 1987. *The Law of Environmental Protection*. City?____________________________: Clark Boardman.

NPPC (Northwest Power Planning Council). 1988.

OTA (Office of Technology Assessment). 1983. *Industrial Energy Use*. OTA, Washington, D.C.

OTA (Office of Technology Assessment). 1986. *Technology, Public Policy, and the Changing Structure of American Agriculture*. OTA, Washington, D.C.

Peddie, R., and D. Bulleit. 1985. Managing Electricity Demand Through Dynamic Pricing. In D. Hafemeister et al., eds. *Energy Sources: Conservation and Renewables*, City?____________________ : American Institute of Physics.

Prindle, W., and M. Reid. 1988. "Pooled" Performance Contracting for Nonprofit Agencies. In *Community and Local Government Conservation Programs: Proceedings of the 1988 ACEEE Summer Study*. ACEEE, Washington, D.C.

Randolph, J. 1988a. The Limits of Local Energy Programs: The Experience of U.S. Communities in the 1980s. In *Proceedings from the International Symposium: Energy Options for the Year 2000.* (University of Delaware)

Randolph, J. 1988b. Waste to Energy Development and PURPA. In *Proceedings from the International Symposium Energy Options for the Year 2000.* (Volume 1).

Renner, M. 1988. *Rethinking the Role of the Automobile*, (Worldwatch Paper #84).

Repetto, R. 1988. *The Forest for the Trees? Government Policies and the Misuse of Forest Resources*. World Resources Institute, Washington, D.C.

Rosenfeld, A. 1985. Managing Electricity Demand Through Dynamic Pricing. In *Energy Sources: Conservation and Renewables*, D. Hafemeister et al., eds. American Institute of Physics. Washington, D.C. .

Rosenfeld, A., 1988. "Energy Conservation, Competition and National Security," *Strategic Planning and Energy Management Journal*, 8:1, 5-30.

Rosenfeld, A., and H. Hafemeister, 1988. "Energy-efficient Buildings," *Scientific American*, 258:4, 78-85.

Ruderman, H., M. Levine, and J. McMahon. 1987. The Behavior of the Market for Energy Efficiency in Residential Appliances Including Heating and Cooling Equipment. *The Energy Journal* 8(1): 101-124.

Shea, C. 1988. Building A Market for Recyclables. *World-Watch*, 1:3, 12-18.

Tripp, J., and D. Dudek. 1986. The Swampbuster Provisions of the Food Security Act of 1985: Stronger Wetland Conservation If Properly Implemented and Enforced. *Environmental Law Reporter* 16:10120-10123.

U.S. DOE (U.S. Department of Energy). 1987a. *Annual Report on Federal Government Energy Management, FY 1987*. U.S. DOE, Washington, D.C.

U.S. DOE (U.S. Department of Energy). 1987b. *Eleventh Annual Report to Congress on Federal Energy Conservation Programs: FY 1987*. U.S. DOE, Washington, D.C.

U.S. DOE (U.S. Department of Energy). 1987c. *Energy Security: A Report to the President of the United States*. U.S. DOE, Washington, D.C.

U.S. DOE (U.S. Department of Energy). 1988. *The Role of Fuel Efficiency in Decreasing Oil Dependence*. (Analysis Memorandum). Office of Policy Analysis, U.S. DOE, Washington, D.C.

U.S. EPA (U.S. Environmental Protection Agency). 1987. *National Air Pollutant Emission Estimates: 1940-1985*. (January). U.S. EPA, Washington, D.C.: EPA.

U.S. EPA (U.S. Environmental Protection Agency). 1988. How Industry is Reducing Dependence on Ozone-Depleting Chemicals. EPA Office of Air and Radiation, Washington, D.C.

Weinberg, A. 1988. Energy Policy in an Age of Uncertainty. *Issues in Science and Technology*. 5:81-85.

Williams, R., E. Larson, and M. Ross. 1987. Materials, Affluence, and Industrial Energy Use. *Annual Review of Energy* 12:99-144.

Wolf, E. 1986. Avoiding a Mass Extinction of Species. In Starke, L., ed., *State of the World 1988*. W.W. Norton, New York, 101-117.

Woodwell, G. 1988. *Biotic Implications of Climate Change: Look to Forests and Soils*. Preparing for Climate Change, Proceedings of the First North American Conference on Preparing for Climate Change: A Cooperative Approach, October 27-29, 1987, Washington, D.C.

WRI (World Resources Institute), World Bank, and UNDP (United Nations Development Programme). 1985. *Tropical Forests: A Call for Action*. WRI, Washington, D.C.

Verdict, M, 1988. "The New Energy Audit Tool: Performance Audits for Energy Management." In *National and Regional Conservation Programs: Proceedings of the 1988 ACEEE Summer STudy on Energy Efficiency in Buildings*. ACEEE, Washington, D.C.

Vine, E., and J. Harris. 1988. The Experience of Energy Conservation Programs With New Commercial Buildings. In *National and Regional Conservation Programs: Proceedings of the 1988 ACEEE Summer Study on Energy Efficiency in Buildings*. ACEEE, Washington, D.C.

USFS (United States Forestry Service). 1987. *The South's Fourth Forest*. Washington, D.C., USFS.

Zimmerman, M., and M. Reid. 1988. "Fact Sheet: Energy and Efficiency in Industry and Commerce," Alliance to Save Energy, Washington, D.C.

CHAPTER IX

INTERNATIONAL COOPERATION TO REDUCE GREENHOUSE GAS EMISSIONS

FINDINGS IX-2

INTRODUCTION IX-4

THE CONTEXT FOR POLICIES INFLUENCING GREENHOUSE GAS EMISSIONS IN DEVELOPING COUNTRIES IX-5
- Economic Development and Energy Use IX-7
- Oil Imports, Capital Shortages, and Energy Efficiency IX-13
- Greenhouse Gas Emissions and Technology Transfer IX-17

STRATEGIES FOR REDUCING GREENHOUSE GAS EMISSIONS IX-18
- International Lending and Bilateral Aid IX-20
  - U.S. Bilateral Assistance Programs IX-21
  - Policies and Programs of Multilateral Development Banks IX-24
- New Directions IX-31

REDUCING GREENHOUSE GAS EMISSIONS IN EASTERN BLOC NATIONS IX-33

U.S. LEADERSHIP TO PROMOTE INTERNATIONAL COOPERATION IX-36
- Restricting CFCs to Protect the Ozone Layer IX-36
- International Efforts to Halt Tropical Deforestation IX-38
- Ongoing Efforts Toward International Cooperation IX-42

REFERENCES IX-45

FINDINGS

- Most of the expected growth in greenhouse gas emissions is from other countries, particularly developing countries and the Eastern Bloc. Efforts to promote international solutions are therefore essential to achieve global reductions in greenhouse gas emissions.

- Technological solutions and policy strategies for the U.S. and other western industrialized nations may not be equally applicable in other parts of the world. Differences in economic development, energy resources, and economic systems must be addressed in devising international strategies to reduce greenhouse gas emissions.

- U.S. leadership has historically made important contributions to other important international environmental agreements, such as the Montreal Protocol on Substances that Deplete the Ozone Layer and the Tropical Forest Action Plan. In the future, U.S. leadership could promote international cooperation to reduce emissions worldwide. Reductions in national emissions may encourage similar actions by other nations and could serve as a valuable demonstration that reductions are feasible.

- Developing countries could reduce the expected increase in greenhouse gas emissions consistent with economic development and other environmental and social goals. Energy efficiency improvements are already essential to reduce capital requirements for the power sector, and efforts to halt tropical deforestation will provide many long-run economic and environmental benefits. The U.S. can promote desirable changes in energy and environmental policy in developing countries through judicious use of its bilateral aid programs and its influence on loans extended by multilateral development banks.

- The Soviet Union and Eastern Bloc nations are and will continue to be important contributors to greenhouse gas emissions. The absence of market pricing has hindered efforts to reduce the energy intensity of these economies but their governments have shown increasing interest in curbing energy costs.

- There have already been some important first steps toward building a framework for international cooperation to reduce the risks of climate change. The November 1988 meeting sponsored by UNEP and WMO initiated a process that includes an intergovernmental committee chaired by the United States to discuss policy responses.

INTRODUCTION

The greenhouse problem requires international strategies to promote global cooperation. An important first step has been taken in this direction under the auspices of the United Nations Environment Programme (UNEP) and the World Meteorological Organization (WMO). In 1988 these organizations helped organize an Intergovernmental Panel on Climate Change to review the science, impacts, and response strategies associated with climate change. The U.S., Soviet Union, China, Japan, and many other leading nations agreed to participate. 'Three panels were organized to consider scientific issues (chaired by the United Kingdom), effects of climate change (chaired by the Soviet Union), and policy responses (chaired by the U.S.). The first meetings are planned for early 1989.

There is an important relationship between the domestic policies discussed in Chapter VIII and the evolution of international cooperation that is the focus of this Chapter. U.S. actions can promote further international cooperation and complementary strategies by other countries. Consideration of the domestic policies reviewed in this report demonstrates that the U.S. no longer views the problem as only a scientific concern. Further analysis and consideration of such policies may also convince other nations of the seriousness of the risks and the need for action. U.S. leadership in the United Nations and other international forums can have a major impact on the evolution of international understanding and ultimately agreements, as illustrated by the Montreal Protocol on Substances that Deplete the Ozone Layer.

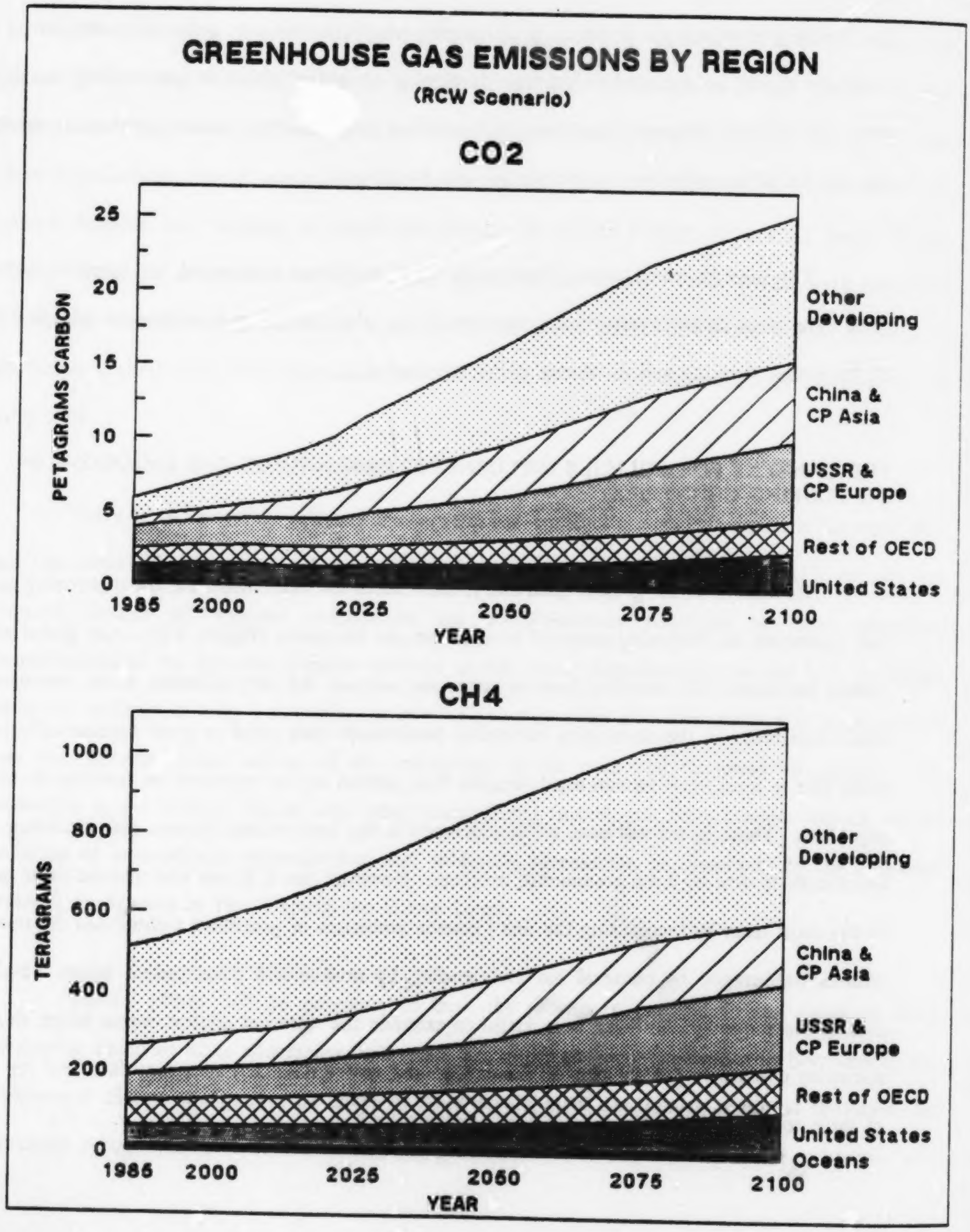
Special efforts will be necessary to limit the growth in greenhouse gas emissions from developing countries while addressing their need for energy and economic growth. Solutions to the problems of climate change may be linked to other development needs, such as capital shortages and increased recognition of local environmental problems. U.S. bilateral assistance programs and participation in multi-lateral development banks (MDBs) provide an opportunity to promote policies that reduce greenhouse gas emissions in developing countries consistent with their development needs. Programs should be designed to increase developing countries' stakes in contributing to this global effort, for example, through debt swaps, afforestation programs, and technology transfer agreements that are linked to reductions in greenhouse gas emissions.

The need for international cooperation has already been recognized, and some important first steps have been taken to establish a framework for international cooperation on scientific aspects of the global warming and to discuss policy responses.

THE CONTEXT FOR POLICIES INFLUENCING GREENHOUSE GAS EMISSIONS IN DEVELOPING COUNTRIES

Because of faster growth rates and greater needs for basic materials, the developing countries will contribute an increasing share of greenhouse gas emissions (Figure 9-1). Any global effort to reduce emissions will therefore have to take into account the very different needs, resources, and other constraints in the developing countries, particularly their need to grow economically in order to be able to meet basic human needs despite their limited capital resources for meeting development objectives. These issues will have to be addressed in the international forums that are being created specifically to deal with the greenhouse problem. However, the U.S. can also address these concerns in the short term by recognizing the link between emissions of greenhouse gases and the investment choices encouraged by bilateral aid and lending by multilateral development banks. Before we discuss these options, however, it is useful to examine the different context within which developing countries operate to get an idea of the energy and environmental issues they face and the priority of their concerns.

FIGURE 9-1


GREENHOUSE GAS EMISSIONS BY REGION
(RCW Scenario)
CO2
PETAGRAMS CARBON
25
20
15
10
5
0
1985
2000
2025
2050
2075
2100
YEAR
Other Developing
China & CP Asia
USSR & CP Europe
Rest of OECD
United States
CH4
TERAGRAMS
1000
800
600
400
200
0
1985
2000
2025
2050
2075
2100
YEAR
Other Developing
China & CP Asia
USSR & CP Europe
Rest of OECD
United States
Oceans

The context for policy formation in developing countries often differs substantially from that in the industrialized countries, reflecting differences in political and economic systems, resources, and societal needs. Some of the major issues associated with the formulation and implementation of energy and related environmental policies in developing countries include socioeconomic equity, financial viability, institutional structure and management of enterprises, and the burgeoning awareness of environmental concerns. Our understanding of these issues is essential to developing emissions reduction policies that are relevant to developing countries, that take into account the conditions existing in these countries and the issues that are of most concern to them.

Economic Development and Energy Use

Developing countries are a much more diverse group than the member countries of the OECD. They range from some of the poorest nations, such as Bangladesh and Ethiopia, to some of the richest ones, such as Saudi Arabia and Singapore. Their annual income per capita varies from $150 to $7000 (World Bank, 1987). The group includes oil and natural gas exporters and importers at different levels of per capita income. Their economies vary from a centrally-planned one like China to more market-oriented ones like Brazil and South Korea. Each country has a different mix of institutions engaged in the supply of energy, reflecting different degrees of governmental control and foreign involvement (Table 9-1).

Equity concerns play a strong role in the pricing of fuels. Preferential electricity tariffs for residential customers are often accompanied by even lower tariffs for agricultural ones. (This is not unlike the situation in some developed countries where low "lifeline rates" are charged for small amounts of electricity consumption.) On the other hand, gasoline prices in developing countries are typically set high relative to world market prices, since gasoline is used in cars that are primarily owned by the rich. Petroleum taxes are an important instrument of social policy that can be adjusted

TABLE 9-1

1985 Population and Energy Use Data from Selected Countries

Country	Population[a] (Millions)	GDP (1985 U.S.$ Billions)	GDP/CAP (1985 U.S.$)	ELECTRICITY Sales Per Capita (KWH)	ELECTRICITY Growth Rate (1970-85) (%)	MODERN FUELS[b] Per Capita (GJ)	MODERN FUELS[b] Growth Rate (1970-85) (%)	Biomass Use Per Capita (GJ)	DOMINANT FUEL Total	DOMINANT FUEL %[c]
China	1,045.3	265.53	254	365	6.7	21.25	5.2	8.83	Coal	79
India	750.9	177.10	236	166	7.2	7.91	5.5	5.79	Coal	56
Brazil	134.6	155.45	1,155	1,283	10.2	35.13	7.3	16.16	Hydro	46
Indonesia	165.2	86.20	522	74	14.3	8.57	11.2	9.28	Oil	71
Korea	41.1	86.80	2,112	1,234	13.4	57.03	8.9	2.07	Oil	49
Nigeria	92.0	48.70	529	68	10.7	7.13	16.4	10.92	Oil	80
Mexico	75.6	146.87	1,943	929	7.9	62.72	7.2	5.28	Oil	58
Egypt	47.2	30.06	637	471	9.9	23.68	8.7	NA	Oil	72
Kenya	20.4	5.02	246	107	10.9	2.31	-3.3	NA	Oil	93
U.S.	239.3	3,946.60	16,492	9,719	3.5	325.76	0.7	11.46	Oil	42

[a] based on several sources

[b] modern fuels expressed as fossil fuel equivalent assuming conversion efficiency of 10,000 Btu/kwh

[c] dominant fuel as a percentage of modern fuels (excluding most biomass)

Source: Lawrence Berkeley Laboratory, August, 1988.

to cushion the impact of energy price increases, or to maintain higher prices when international prices decline.

The price of coal in India and China, the two major developing countries that rely heavily on coal, is subsidized with subsidies varying by sector. In China, since the coal price is too low, the government provides subsidies varying from 10 to 27 yuan/ton (or $2.7 to $7.2) to coal producers in order to encourage them to produce more coal (Dadi, 1988). Similarly, despite continual increases in the price of coal in India, Coal India Limited (CIL), an Indian government enterprise that produces over 90 percent of the country's coal, incurred losses equivalent to more than $8 per ton (Hindu Survey, 1988).

Industrial energy use forms a major segment of overall energy use in the developing countries. Because the industries are generally less modern than their counterparts in the developed countries, they tend to be less energy-efficient as well (Table 9-2). According to AID, developing countries can typically save 5-15 percent of commercial fuel through low cost measures and up to 25 percent through cost-effective retrofits (U.S. AID, 1988). A recent detailed study of the potential for cost-effective electricity conservation in Brazil documented potential savings equal to more than a fourth of currently-forecasted needs (Geller et al., 1988; see Table 9-3). The management of government-controlled industries is often inefficient, as a comparison of similar products produced by government-controlled and private-sector industries, even in the same country, will show.

Given adequate capital and technical knowledge, industries in a developing country can operate just as efficiently as comparable ones in a developed country (Schipper, 198?). For example, multinational companies operating in developing countries often use about the same amount of energy per unit of output as the company's comparable plants in the developed countries.

TABLE 9-2

Efficiency of Energy Use in Developing Countries: 1984-85

Country/Region	Energy Use/ Unit of GDP[a]	Average Annual Growth Rate (%)
North America[b,c]		
Canada	0.80	-0.5
United States	0.61	-2.2
Average	0.62	-2.1
Oceania[b,c]		
New Zealand	0.50	+1.8
Australia	0.45	-0.5
Japan	0.29	-3.1
Average	0.32	-2.5
Europe[b,c]		
Luxembourg	0.65	-4.9
Turkey	0.56	-1.0
Portugal	0.49	+1.5
Greece	0.44	+1.2
Ireland	0.44	-1.4
Norway	0.40	-1.4
Sweden	0.40	-0.6
Belgium	0.36	-2.2
Netherlands	0.36	-1.7
United Kingdom	0.35	-2.0
Austria	0.33	-1.2
Italy	0.33	-1.8
Spain	0.32	+0.3
Germany	0.31	-1.7
Denmark	0.27	-1.7
Switzerland	0.25	+0.3
Average	0.34	-1.4

TABLE 9-2 (continued)

Efficiency of Energy Use in Developing Countries: 1984-85

Country/Region	Energy Use/ Unit of GDP[a]	Average Annual Growth Rate (%)
Asia[d,e]		
People's Republic of China	1.40	-1.3
India	0.79	+1.4
Pakistan	0.64	+4.2
Taiwan	0.62	+0.2
Thailand	0.38	-0.8
Malaysia	0.36	+0.3
Indonesia	0.35	+3.3
Philippines	0.35	-2.7
Bangladesh	0.27	NA
Average	0.97	+0.5
Latin America[d,e]		
Venezuela	1.40	+4.6
Brazil	0.68	+2.1
Mexico	0.56	+2.2
Argentina	0.29	+1.8
Average	0.57	+2.7
West Africa[d,f]		
Senegal	0.49	+3.6
Morocco	0.27	0.0
Nigeria	0.18	+9.4
Cote d'Ivoire	0.13	+2.8
Average	0.20	+6.5

[a] Gross domestic product metric tons of oil equivalent per $1,000 U.S. (constant 1980 dollars).
[b] 1985 data.
[c] Average annual growth rate for 1973-85.
[d] 1984 data.
[e] Average annual growth rate for 1973-84.
[f] Average annual growth rate for 1977-84.

NA = Not available.

Sources: Sathaye, et al., 1987; OECD/IEA, 1987.

TABLE 9-3

Potential for Electricity Conservation in Brazil

End-Use Area	Current forecast (TWh)	Savings potential (%)	Savings potential (TWh)
Industrial motors	164.8	20	33.0
Domestic refrigerators	24.7	60	14.8
Domestic lighting	16.5	50	8.2
Commercial motors	28.0	20	5.6
Commercial lighting	25.0	60	15.0
Street lighting	16.8	40	6.7
Total	275.8	--	83.3

Source: Geller et al., 1988.

The energy sector is owned and operated by government-controlled corporations in the poorer developing countries. These corporations often have little incentive to invest in reducing their energy costs because they are protected from competition and rewarded more by measures of production than efficiency of service. This is compounded by regulated prices that are often not high enough to pay for the companies' expenses and non-payment or delayed payment for fuels purchased from other government companies.

Oil Imports, Capital Shortages, and Energy Efficiency

Most developing countries are largely dependent on imports for commercial fuels. During periods of high oil prices, import costs have resulted in serious hardship in these countries. In some countries oil import costs exceeded 25 percent of export earnings in 1984 and much more than that in earlier years (Table 9-4). Future increases in world oil prices may have an even more adverse impact because of the rapid growth in the transportation sector in some countries.

A shortage of capital for large development projects is pervasive in developing country economies and increasingly a constraint on the energy sector. Energy investments in developing countries require a high percentage of available capital (Table 9-5). The World Bank and more recently AID have reviewed the magnitude of energy shortfalls in developing countries and its implications for economic development (World Bank, 1983; U.S. AID, 1988; see Table 9-6). AID estimates that in a current trends scenario, AID-assisted countries would need to spend over $2.6 trillion for the power sector by the year 2008 to meet projected needs. This is an average of over $125 billion per year, compared with the estimated $50 to $60 billion currently being spent annually. Since current expenditures already consume a fourth or more of development budgets, this is potentially a serious constraint on economic development. Aggressive conservation efforts could reduce capital needs by 40-60 percent (Williams, 1988; World Bank, 1983).

TABLE 9-4

Net Oil Imports and Their Relation to Export Earnings for Eight Developing Countries, 1973-1984

Net Oil Imports
(million U.S. dollars, current prices)

	1973	1974	1977	1979	1981	1983	1984
Kenya	1	27	57	113	316	208	219
Zambia	11	30	53	72	63	274	454
Thailand	173	510	806	1,150	2,170	1,740	1,480
Korea	276	967	1,930	3,100	6,380	5,580	5,770
Philippines	166	570	859	1,120	2,080	1,740	1,470
Brazil	986	3,230	4,200	6,920	11,720	8,890	7,470
Argentina	83	328	338	351	302	-	-
Jamaica	71	193	242	309	490	-	-
India	308	1,170	1,750	3,067	-	-	-
Bangladesh	-	92	172	247	509	286	314
Tanzania	47	153	102	174	306	175	156
Imports as Percentage of Export Earnings							
Kenya	0.1	4.1	4.8	10.2	26.9	21.2	20.3
Zambia	2.2	5.1	9.5	8.2	7.8	20.8	21.4
Thailand	11.1	20.9	23.1	21.6	30.9	27.3	20.0
Korea	8.6	21.7	19.2	20.6	30.0	22.8	19.7
Philippines	8.8	20.9	27.5	24.4	36.8	35.4	27.8
Brazil	15.9	40.7	34.7	45.4	50.4	40.6	27.7
Argentina	2.5	8.3	6.0	4.5	3.3	-	-
Jamaica	18.1	27.3	32.4	37.7	50.3	-	-
India	10.6	29.7	27.5	39.3	-	-	-
Bangladesh	-	26.5	36.1	37.4	64.6	39.4	33.6
Tanzania	12.8	38.0	20.2	34.8	52.7	47.0	42.3

Source: IMF, 1985 in Goldemberg et al., 1987.

TABLE 9-5

Annual Investment in Energy Supply As a Percent of Annual Total Public Investment (Early 1980s)

Under 20%	20-30%	30-40%	Over 40%
Egypt	Botswana	Ecuador	Argentina
Ethiopia	China	India	Brazil
Ghana	Costa Rica	Pakistan	Columbia
Nigeria	Liberia	Philippines	Korea
Sudan	Nepal	Turkey	Mexico

Source: Munasinghe and Saunders, 1986.

TABLE 9-6

World Bank Estimate of Capital Requirements for Commercial Energy In Developing Countries, 1982-1992

	Low Income	Middle Income		All Countries
		Oil Importers	Oil Exporters	
Total Required Capital				
Electricity	17.6	35.9	13.1	66.6
Oil and Gas	12.1	16.7	40.0	68.8
Coal	5.6	2.8	0.6	9.0
Total	35.3	55.4	53.7	144.4
Foreign Exchange Requirements				
Electricity	3.6	11.4	7.2	22.2
Oil and Gas	4.9	5.9	25.4	36.2
Coal	1.1	1.0	0.3	2.4
Total	9.6	18.3	32.9	71.2[a]

[a] Includes $10.4 billion for refineries that is not included in country group or individual fuel totals.

Source: The World Bank, 1983.

The added cost of more efficient products is often cited as an obstacle to efforts to improve efficiency in capital-short developing countries. However, the high cost of capital may favor investments in efficiency relative to investments in long lead-time supply projects, such as construction of new powerplants. Because efficiency investments pay-off much more quickly, their economic advantage increases with interest rates (Geller, 1987). However, this comparison is not visible to consumers who are not paying the marginal cost of new energy supplies, and energy and utility companies may have no interest in efficiency for institutional reasons (Goldemberg et al., 1987).

Greenhouse Gas Emissions and Technology Transfer

The transfer of state-of-the-art technology will be necessary to significantly reduce commercial energy use in developing countries. However, there are many obstacles to the development and dissemination of such technologies from industrialized countries to potential competitors in developing countries.

Even when state-of-the-art technology is made available, developing country governments or manufacturers may be reluctant to accept it. Such technology will carry a higher capital cost and may produce products of higher quality at a higher price. Heavily-indebted developing countries may not be in a position to secure the additional capital needed for state-of-the-art technology. Developing country markets tend to be more price-sensitive given the lower discretionary income enjoyed by consumers in these countries. A program to reduce the cost of capital for more efficient plants and equipment, and another to induce consumers to purchase products with higher first-costs yet lower lifecycle costs are essential to encourage developing country consumers to acquire and use state-of-the-art technology.

Most developing countries need technologies that take advantage of abundant but unskilled labor and that minimize the need for capital, and many have more biomass resources than fossil fuels (Goldemberg et al., 1987; Williams, 1988). Improved versions of some low-cost technologies no longer used in the industrialized countries, such as wood-burning cookstoves, are therefore a high priority. Developing countries are still rapidly increasing their consumption of basic materials, whereas such consumption is being replaced by high value-added fabrication and finishing activities in industrialized countries (Williams et al., 1987). This implies substantial differences in research priorities, but there are few institutions and much less money devoted to meeting their needs. The tendency, reinforced by the risk-averse policies of multilateral banks, is to make do with what is tried and true in the industrialized nations.

STRATEGIES FOR REDUCING GREENHOUSE GAS EMISSIONS

Studies of future energy use in developing countries indicate that the industrial sector and power generation will retain their large share of total energy demand (Sathaye et al., 1988). However, the mix of fuels is less certain. A slower growth rate would mean continued use of traditional, and therefore, biomass fuels. On the other hand, faster economic growth would reduce this burden, but it would add to that caused by transportation, as individuals with higher income would demand greater mobility and consequent higher consumption of petroleum products. Strategies to reduce CO_2 emissions will therefore depend on the rate of economic growth in the developing countries.

Energy-pricing reform is essential to promote efficient use of fuels; existing subsidies and price controls are major barriers to investments in energy conservation. However, the short-term result may not be to reduce CO_2 emissions since many countries have substantial unmet needs that would utilize any supplies made available by efficiency improvements. Coal is also the least expensive fuel other than biomass in most developing countries, and market pricing may lead to increasing the share of energy from this carbon-intensive source.

AID, the World Bank, and other development agencies have actively promoted energy-pricing reform in developing countries. However, a recent AID analysis concludes that such efforts have often failed due to fears that reforms will be economically and politically destabilizing. However, effective pricing reform does not necessarily require radical reorganization of economies. Hungary, for example, has achieved substantial improvements in agricultural productivity by creating economic incentives while maintaining a primary role for cooperatives (Chandler, 1986). Further study may help identify ways to overcome this problem, but a realistic expectation may be gradual price increases and structural reform to reduce future interference in energy markets (U.S. AID, 1988).

Improvements in energy efficiency in developing countries may not lead to emission reductions in absolute terms because the energy made available may meet unmet needs and pent up demands. This is consistent with efforts to promote economic growth but implies that even highly successful conservation programs may not avoid substantial emissions growth in these countries. However, over the long run the result will be less emissions than would result from continued inefficient use of energy. Pricing reform similarly may not always lead to reduced emissions of greenhouse gases. For example, removing subsidies for kerosene and LPG may push some consumers back to inefficient use of traditional fuels (Leach, 1987, 1988). This may promote deforestation and a net increase in CO_2 emissions if the only alternative is wood from freshly-felled trees. Continued subsidies for modern cooking fuels for some transition period might be desirable in order to reduce CO_2 emissions.

Several financial strategies can promote improved industrial efficiency by increasing the capital available for desired investments. One traditional financial approach is to allocate capital for designated purposes, such as improving energy efficiency, sometimes at subsidized rates. Power sector loans also could be tied to stringent conservation targets involving utilities in promoting conservation as in some industrialized countries. Governments also sometimes deliberately seek to increase competition within the industrial sector, sometimes inviting foreign collaboration, as a way of forcing companies to increase capital spending.

As capital becomes expensive, governments have begun to tap into private capital markets by floating bonds in targeted funds (e.g., the Korean, Taiwanese, or Indian funds introduced in international markets). Domestic markets are being tapped as well in similar ways. Governments could target private capital for proven technologies and government funds for investment in novel, yet economic, energy conservation schemes specially targeted to reduce CO_2 emissions. Industrialized countries may help by inducing banks to reduce the interest charged for investment targeted for CO_2 emissions abatement strategies.

Another possible innovative approach is for governments to allow the release of so-called "black money" funds locked away by private individuals to evade taxes, if directed to investments for CO_2 emissions abatement. In some countries black money may account for 30-40 percent of total GDP (*Economist*, August, 1988). Placing this money in circulation would mean that governments would have to forego or reduce taxes on these funds, in effect conceding that they would not collect them anyway without substantial increase in enforcement.

International Lending and Bilateral Aid

The U.S. can help developing countries reduce their greenhouse gas emissions through its foreign aid programs and contributions to the World Bank and other multilateral development banks (MDBs). Although all such programs (U.S. and foreign) address only a small percentage of total investment in developing countries, they can exert disproportionate influence because they leverage much greater amounts of funds and certify the financial merit of particular technologies and projects.

U.S. Bilateral Assistance Programs

Most U.S. non-military bilateral assistance is administered by the Agency for International Development (AID), including energy- and forestry-related assistance. AID has attempted to improve its sensitivity to environmental concerns in recent years and estimates that it now spends over $100 million for activities aimed at conserving natural resources (U.S. AID, 1987). The Agency has expanded the number of environmental professionals and established an Office of Forestry, Environment, and Natural Resources.

Most AID support for energy is provided through regional and national programs, although a few projects are funded through a central Office of Energy. Some coordination is also encouraged by an Agency Sector Council for Energy and Natural Resources. Energy-related funding for the past five years has averaged slightly less than $200 million per year; the FY 1986 budget included $254 million for energy projects in 23 countries, of which $180 million was spent for electric power (U.S. AID, 1988). This is about 4 percent of the total AID budget, much less than the share allocated to energy by the World Bank and many other bilateral aid programs (Gray et al., 1988).

AID has funded some analysis of promising projects for biomass fuels that indicate the possibilities for redirecting some bilateral assistance to more effectively promote rational energy planning and development and adoption of improved technology. The Multi-Agency Working Group on Power Sector Innovation, coordinated by AID's Office of Energy, was organized in 1987 to promote cooperation among international institutions involved in power sector development. AID has proposed using this group and the International Development Assistance Committee to focus greater attention on the energy/environment relationship (U.S. AID, 1988). Proposals have also been made to expand the scope of the Consultative Group on International Agricultural Research, a highly successful international consortium of lenders for improving crop yields and production in developing countries, to encompass agroforestry, bioenergy, and tropical ecology.

Current AID priorities are to identify projects that utilize indigenous energy resources and that have the greatest potential for replication. AID will attempt to broker technical and financial assistance for promising projects, emphasizing private sector participation. AID's funding priorities are also shifting toward the poorest nations, which generally implies countries with lower energy growth rates - although sometimes high rates of deforestation (Gray et al., 1987). AID is proposing to give greater attention to the environmental implications of the energy sector

AID has steadily upgraded its commitment to forestry in recent years, from about $20 million in 1979 to $56.2 million for 146 projects in FY 1987 (U.S. AID, 1987; Stowe, 1987; Table 9-7). Agroforestry has been emphasized along with training and institution building. A large amount of support has been given to tree planting and forestry-related activities through the Food for Peace Program (PL 480); the program is responsible for direct tree planting on an estimated 1.5 million hectares in 53 countries during the early 1980s (Joyce and Burwell, 1985) and for 38 tree-planting projects in 23 countries in FY 1987, mostly in Africa (U.S. AID, 1988). Combining bilateral and food-aid assistance, AID's tropical forestry programs exceeded $82 million in FY 1987. AID has also been a strong supporter of the Tropical Forest Action Plan.

If the U.S. seeks to promote reductions in greenhouse gas emissions in developing countries, AID would logically play a major role. Section 106 of the Foreign Assistance Act already authorizes AID programs to promote renewable energy and improvements in energy efficiency. Several proposals have been made for greatly expanded efforts in this area. A working group of the Atlantic

TABLE 9-7

U.S. AID Forestry Expenditures by Region

Region	Number of Countries With Projects	Number of Projects Active in FY 1987	Number of New Starts	Number Completed	LOP Forestry Obligations (in $1,000)	FY 1987 Forestry Obligations (in $1,000)
Africa	23	45	3	3	95,150	13,960
Asia/Near East	11	39	1	6	273,212	17,337
Latin America/ Caribbean	12	46	3	8	140,241	17,398
Central Bureaus	NA	16	0	0	78,103	7,488
Totals	46	146	7	17	$586,706	$56,183

Note: Many forestry projects are components of larger natural resource and agricultural projects. To determine the forestry component, a percentage of the total LOP funding was estimated for significant forestry activities based on judgments made by A.I.D. staff and contractors. This percentage was then applied to each year's obligations to arrive at annual figures. Projects can receive funding obligations at any time during the life of the project.

Source: IDEA Inc., 1988.

Council of the United States and the Member Committee of the U.S. World Energy Conference recommended expanding AID's energy assistance programs to promote greater private-sector investment. They suggest using the revolving loan fund and grant program administered by the Bureau for Private Enterprise to make energy loans; its current priority is agri-business (Gray et al., 1988).

Another recent study by the American Council for an Energy-Efficiency Economy proposes that AID's energy budget be increased to $50-$100 million per year. The authors would redirect aid programs away from support of specific projects in favor of building the capabilities of individuals and institutions within developing nations. They conclude that increasing private-sector involvement should be a high priority, noting that U.S. companies could be encouraged to market energy-efficient technologies with the assistance of the Overseas Private Investment Corporation, the Export-Import Bank, and the Trade and Development Program (Chandler et al., 1988).

AID is not the only U.S. agency involved in bilateral assistance. For example, both the Department of Agriculture and the Peace Corps support international cooperative forestry programs. The former has an Office of International Cooperation and Development exclusively devoted to international activities and also funds some research (Stowe, 1987).

Policies and Programs of Multilateral Development Banks

The U.S. contributes over $1 billion to MDBs annually, an amount that leverages many times as much actual borrowing through co-financing and other arrangements. Much of the activity of these banks is directly or indirectly related to greenhouse gas emissions through loans for energy projects, forestry, and agriculture. U.S. influence on these institutions is substantial, though they are not controlled by the U.S. government. Voting on each bank's board is through a board of

TABLE 9-8

World Bank Energy Sector Loans in 1987
(Million U.S. Dollars)

	Eastern & Southern Africa	Western Africa	East Asia & Pacific	South Asia	Europe, Middle East & N. Africa	Latin America & Caribbean	Total
Oil/gas/coal	20.0	15.0	0.0	548.0	0.0	104.4	687.4
Hydroelectric	63.0	6.3	684.8	1,312.0	527.0	423.8	3,016.9
Total	83.0	21.3	684.8	1,860.0	527.0	528.2	3,704.3

Source: World Bank, 1987.

directors whose membership is proportional to the size of contributions, giving the U.S. _____ percent in the World Bank. (U.S. recommendations on specific loans, however, have been outvoted.) The U.S. is the largest contributor to the Bank, and the Bank president has traditionally been an American. Congress has directed use of the U.S. "voice and vote" to promote several selected policies, such as human rights concerns and the use of "light capital technologies" (22 U.S. Code Sec. 262f and 262d).

The MDBs are able to influence the policies of developing countries to some degree because loans and aid tend to be offered on relatively favorable terms and bank support can help countries obtain credit from lenders. MDB lending has taken on even greater significance as the debt burden and capital requirements of developing countries have grown enormously in recent years. This influence has been used in ways that have had both positive and negative impacts on the energy and forestry sectors. For example, the World Bank has been a strong advocate of energy-pricing reforms (World Bank, 1983; Goldemberg et al., 1988). However, studies have also documented numerous MDB projects that lead directly and indirectly to deforestation, including roads, dams, tree crop plantations, and agricultural settlements (Repetto, 1988).

About one-fourth of World Bank lending goes to energy-related projects, or nearly $4 billion. The rate for other MDBs ranges from 9 percent by the African Development Bank to 34 percent for the Asian Development Bank (Gray et al., 1988). Traditionally, a majority of this funding has gone for development of very large power projects (Table 9-8). By one estimate, over 90 percent of multilateral and bilateral energy assistance has been for large systems for the generation, transmission, and distribution of electricity; new and renewable energy sources have received about 3 percent and end-use efficiency measures less than 1 percent of total energy-related loans (Goldemberg et al., 1987; see Table 9-9).

TABLE 9-9 (continued)

Expenditures of Multilateral and Bilateral Aid Agencies in the Energy Area (millions of current dollars)

	Conventional Power Generation (Hydro, Nuclear, Thermal), Transmission; Distribution; Power Sector Studies	Fossil Fuels Recovery (includes Studies and Training)	New and Renewables (includes Geothermal, Fuelwood)	Technical Assistance, Energy Planning, Other	Total Energy Aid
BILATERAL AID					
French Aid (1976-1979)	229	16	30	5	280
Canadian International Development Agency (1978-1979, 1979-1980)	88	0	2	1	91
German Aid (1970-present)	1,925	41	81	48	2,095
Kuwait Fund (FY 1973-FY 1978)	437	99	1	-	536
Netherlands-Dutch Development Cooperation (1970-present)	119	71	7	2	198
U.K. Overseas Devel. Admin. (1973-present)	146	1	3	-	149
U.S. AID (FY 1978-FY 1980)	403	2	96	46	546
Grand Total	12,719	757	437	121	14,033
Percentage in Each Sector	91	5	3	1	100

Source: Goldemberg et al., 1987.

TABLE 9-9

Expenditures of Multilateral and Bilateral Aid Agencies in the Energy Area (millions of current dollars)

	Conventional Power Generation (Hydro, Nuclear, Thermal), Transmission; Distribution; Power Sector Studies	Fossil Fuels Recovery (includes Studies and Training)	New and Renewables (includes Geothermal, Fuelwood)	Technical Assistance, Energy Planning, Other	Total Energy Aid
MULTILATERAL AID					
World Bank (FY 1972-December 1978)	5,210	305	170	-	5,686
Inter-American Development Bank (FY 1972-FY 1978)	2,596	158	4	-	2,758
Asian Development Bank (FY 1972-FY 1978)	1,183	21	0	-	1,204
European Development Fund (to May 1978)	141	-	9	-	150
U.N. Development Programme (to Jan. 1979)	72	23	29	13	137
U.N. Center for Natural Resources, Energy and Transport (to Jan. 1979)	3	5	4	5	17
Subtotal	9,205	512	216	18	9,952

The World Bank has had a major role in financing energy sector expansion in the developing countries that are growing most rapidly and relying most heavily on fossil fuels, including China, India, and Pakistan. Coal resources in these countries are often characterized by low heating values and the generation and distribution of electricity is typically much less efficient than in the industrialized countries. Bank projects, therefore, represent a large share of carbon emissions from developing countries.

In 1987 the World Bank announced a general commitment to upgrade its support for environmental analysis and programs (World Bank, 1987). The Bank has created a new environmental department, increased environmental staff, and begun a process of preparing environmental assessments on about 30 developing countries. Special attention is being given to identifying regional environmental projects in Africa. Support for tropical forest conservation and development has also been made a high priority; funds will increase from $152 million in FY 1987 to $350 million in FY 1989.

Some power sector loans have important conservation components; for example, a recent loan to Zimbabwe includes $44 million to upgrade generating equipment, rehabilitate transmission lines, and train workers to increase total output (*World Bank News*, January 14, 1988). The Bank has used its influence to support energy-pricing reforms and the elimination of subsidies and has funded a small number of conservation programs through its Energy Sector Management Assistance Program (Table 9-10). Some industrialization loans may also result in substantial improvements in energy efficiency, although such improvements are not a primary purpose for these loans.

The Bank plans to maintain energy loans as a relatively constant percentage of its total lending (Gray et al., 1988). However, recognizing that capital needs for energy in developing countries are expected to grow much faster than available funding, the Bank plans to increase its analytical, policy, and technical advisory roles and to become more of a catalyst for funds from

TABLE 9-10

World Bank Energy Conservation Projects:
Energy Sector Management Assistance Program (ESMAP)
Energy Efficiency Initiatives

Industrial Energy Efficiency

- Program Design and Institutional Support (Senegal, Ghana)
- Energy Audits (Syria)
- Training of Local Staff (Tanzania)

Power Efficiency (Many Countries)

- Design of Programs to Reduce Technical and Non-Technical Losses
- Pre-Feasibility Studies for Life Extension and Rehabilitation Projects
- Utility Organization Studies

Electricity Savings in Buildings

- Energy Efficient Building Code (Jamaica)
- Appliance Labeling (Jamaica)

Household Energy Savings

- Household Energy Strategy Studies
- Improved Cookstoves Projects
- Improved Charcoaling

Energy-Environmental Studies

- Energy Supply Options to Steel Industry in Carajas Region (Brazil)

Source: WRI, 1988a

non-Bank sources. The Bank, like AID, plans to give more attention to private power generation and other innovative means of financing new power sources.

A Bank representative cited several obstacles to increased support for conservation at an EPA workshop (WRI, 1988a). One is that the Bank traditionally has found it difficult to fund relatively small projects; ways must be found to package them as an element of a larger loan. (This was done in the case of a large power loan to Brazil, which included $2 million for analysis of conservation opportunities.) Implementation of projects that require actions by many individuals is similarly perceived as difficult. Some of the most inefficient industries may be judged uneconomic and therefore inappropriate candidates for loans. Finally, the recipient governments have to be interested and must possess the necessary technical skills to implement conservation programs.

Another problem is the availability of proven technology suited to the needs of developing countries. As discussed above, the technological needs of developing countries differ from the industrialized countries in many areas. However, lending criteria tend to discourage the search for new or innovative technologies by restricting financing to practices that have been fully proven in practice (Daffern, 1987). This reflects an understandable desire to minimize risks, but the effect is often to finance equipment that is not the most efficient. Promising alternatives that would utilize biomass and other local resources are also neglected because the technologies are not widely used in the industrialized countries (Williams, 1988).

New Directions

The possibility of redirecting bilateral aid and Bank loans to further energy conservation and other strategies to reduce greenhouse gas emissions was discussed at the EPA workshop on developing country issues. One proposed remedy is a shift in Bank energy sector lending to general energy programs as opposed to specific projects as a way of facilitating more funding of demand-side efforts (Goldemberg et al., 1988). This proposal may be difficult to implement but may receive more attention as capital constraints lead to greater interest in conservation.

A recent study of innovative financing mechanisms by the World Resources Institute proposes that the MDBs place greater emphasis on promoting policy reforms in conjunction with loan agreements to protect natural resources. The authors suggest that the international development agencies identify and analyze the effects of tax, tariff, credit and pricing policies, as well as the terms and administration of concession agreements, on the use of resources (Repetto, 1988, p. 41).

A possible strategy for creating an economic incentive for protection of tropical forests involves payment of annual fees for custodian services--protection from squatters and illegal development--to affected nations in proportion to the areas under protection (Rubinoff, 1985). Agreements to protect 100 million hectares, or roughly 10 percent of the world's remaining moist tropical forest, might cost on the order of three billion dollars. The status of reserves would be monitored and payments adjusted accordingly. In this way tropical countries would be paid for some management costs, reflecting some of the benefits thereby provided to the rest of the world.

Section 119 of the Foreign Assistance Act requires AID to prepare environmental assessments of its major actions, including effects on the global environment.[1] AID is also specifically directed to consider the impacts of its programs on tropical forests (22 CFR § 2151(a), (p); see also Stowe, 1987, p. 73-74).

---

[1] AID procedures for preparing environmental assessments are published in the Code of Federal Regulations, Volume 22, Part 216.

The importance of these issues is suggested by increasing Congressional interest (Stowe, 1987; Rich, 1985, p. 681). Section 539 of Public Law 99-591 directs the Secretary of the Treasury to instruct U.S. Executive Directors in each of the multilateral development banks to take a number of steps to support environmental reform measures and also requires the Treasury Department to report on progress toward these objectives (U.S. Treasury Department, 1988). The Department's most recent report provides mixed reviews of the MDBs' responsiveness to environmental concerns. As already noted, the World Bank announced a higher priority for environmental concerns in 1987, but the report states that "The Bank has not moved effectively in the area of energy conservation."

REDUCING GREENHOUSE GAS EMISSIONS IN EASTERN BLOC NATIONS

The Soviet Union is the third largest source of carbon dioxide emissions and together with Eastern European nations is likely to remain a significant contributor to global greenhouse gas emissions in the years to come (Figure 9-1). The energy policies of these countries will therefore have an important influence on the greenhouse problem.

The Soviet Union has enormous energy resources, although much of it, including half the world's accessible coal, is in relatively remote areas of Siberia. Soviet oil production is roughly equal to the total production of all Middle Eastern countries combined and the Soviets also rank first in gas production and third in coal production. Coal was the dominant energy source until the late 1950s but declined to less than 30 percent in 1977 with the growth in oil production (Table 9-11). Future plans call for increasing reliance on natural gas and nuclear power and renewed growth in coal use; large coal-burning powerplants and coal slurry pipelines are now under construction. Other Eastern European nations, particularly Poland, East Germany, and Czechoslovakia, are even more dependent on coal (WRI, 1988).

TABLE 9-11

Energy Use in the Soviet Union and Eastern Bloc (petajoules)

	Liquid Fuels[a]			Solid Fuels			Gaseous Fuels[b]			Electricity[c]			Total		
	1970	1980	1985	1970	1980	1985	1970	1980	1985	1970	1980	1985	1970	1980	1985
Eastern Europe															
Bulgaria	346	575	562	570	615	672	17	148	216	7	49	71	940	1,387	1,521
Czechoslovakia	371	668	567	1,792	1,861	1,878	79	298	330	25	40	71	2,267	2,867	2,846
East Germany	483	690	632	2,602	2,523	2,856	22	302	288	8	54	53	3,065	3,569	3,829
Hungary	223	424	392	496	374	373	121	364	393	13	27	63	853	1,189	1,221
Poland	301	610	512	2,878	4,230	4,170	222	363	363	7	11	6	3,408	5,214	5,051
Romania	406	688	760	410	689	813	971	1,507	1,599	1	47	51	1,788	2,931	3,223
Subtotal	2,080	3,655	3,425	8,748	10,292	10,762	1,432	2,982	3,189	61	228	315	12,321	17,157	17,691
U.S.R.R.	9,283	14,770	14,450	12,933	14,440	14,596	6,611	13,209	19,761	442	811	1,257	29,270	43,229	50,065
Total	11,363	18,425	17,875	21,681	24,732	25,358	8,043	16,191	22,950	503	1,039	1,572	41,591	60,386	67,756

Notes:

[a] All petroleum products and natural gas liquids.
[b] Natural gas, manufactured gas, coke-oven gas, and blast furnace gas.
[c] Hydro, nuclear, and geothermal power.

Source: WRI, 1988.

The energy intensity of the Soviet economy changed relatively little between 1970 and 1985, in contrast with the substantial reductions achieved during the same period in the U.S. and other industrialized nations. The government has become increasingly interested in energy conservation because of the growing capital and fuel costs of energy production. More than 20 percent of national capital investments and 14 percent of primary energy resources are consumed by the energy supply system (NAS, 1987). Oil is also a valuable export commodity, and known reserves may be exhausted at current production rates by the year 2000. Siberian reserves may be large but production costs will be much higher (WRI, 1988).

According to a recent report by a Soviet energy expert, improvements in energy efficiency continue to prove elusive contrary to official progress reports (Martynenko, 1988). This is because industry does not pay market prices for energy and therefore has little economic incentive to conserve. However, the government is gradually increasing fuel costs within the Soviet economy and recent economic reforms may give industry greater incentive to conserve (NAS, 1987).

Energy pricing and planning in Eastern Europe is complicated by trade agreements with the USSR. These countries have provided labor for construction on Soviet oil and gas projects in return for options to purchase oil at a price equal to the average price paid for Soviet oil exports over the previous five years--a rewarding arrangement when prices were rising but unattractive at recent low oil prices (WRI, 1988).

The Soviet Union and United States currently have cooperative agreements on both climate change and energy conservation. The U.S.-USSR Agreement on Cooperation in the Field of Environmental Protection lists numerous projects on atmospheric science. The first U.S.-USSR Symposium on Energy Conservation was held in Moscow in June 1985 and several meetings followed, most recently in October 1988. A program of cooperative research has been developed, administered in the U.S. by the National Academy of Sciences (NAS, 1987; Memorandum of the Soviet-American Symposium, 1988). The Soviet Union has also independently expressed strong interest in global climate change problems. At the November 1988 meeting on global climate issues in Geneva sponsored by WMO and UNEP, the Soviet Union agreed to chair a panel on the effects of climate change.

U.S. LEADERSHIP TO PROMOTE INTERNATIONAL COOPERATION

The international and bilateral cooperation already in place has established a solid foundation for discussion of policy responses; however, there is much that needs to be done before this discussion and analysis leads to agreement on necessary actions. Several precedents suggest that U.S. leadership can help achieve agreement on response strategies. Two important sources of greenhouse gas emissions, the use of CFCs and tropical deforestation, have already been the subject of international agreements that should moderate global warming. In both cases, action was taken for reasons largely unrelated to climate change, but examination of the evolution of these agreements may suggest factors conducive to agreement on climate change.

Restricting CFCs to Protect the Ozone Layer

In September 1987, twenty-four nations signed an agreement in Montreal (the Montreal Protocol) to reduce emissions of CFCs 50 percent by 1999 because of growing concern about the effect of these chemicals on stratospheric ozone. The reductions are to be achieved through a phased process beginning with a freeze six months after the Protocol goes into effect (January 1, 1989, or shortly thereafter) and a 20 percent reduction by July, 1993. The U.S. ratified the Montreal Protocol on April 21, 1988. EPA issued regulations consistent with the requirements of the Protocol on August 1, 1988 (*Federal Register*, Aug. 12, 1988). For a description of the terms of the Protocol and

U.S. regulations, see **REGULATIONS AND STANDARDS** in **CHAPTER VIII**. These regulations also will go into effect at the time the Protocol takes effect.

Aside from its direct impact on reducing emissions of important greenhouse gases, the terms of the Protocol and the process that led up to the agreement offer some valuable insights for cooperation to address climate change. Developing nations, which currently use only about 15 percent of CFCs, were concerned that emissions reductions might hinder their economic growth. Therefore, to encourage their participation, Article 5 of the Protocol allows countries with consumption less than 0.3 kg per capita to delay compliance by 10 years so long as they do not exceed that amount. (U.S. CFC consumption was more than 1 kg/capita in 1985). The industrialized countries also agreed to provide technical assistance and financial aid in support of developing countries' efforts to adopt alternatives.

The Protocol was negotiated over a two-year period, but the foundations were laid over a period of a decade or more. Intergovernmental meetings were first held in 1977 and 1978 (Stoel et al., 1980). A consensus-building scientific process, the Coordinating Committee on the Ozone Layer, was created by the UNEP Governing Council in 1977. The Council decided to convene a working group of legal and technical experts in 1981, and the first meeting took place in January 1982. When agreement on proposals for action at first proved impossible, the participants came to an agreement in March 1985 that provided a framework for scientific cooperation: the Vienna Convention for Protection of the Ozone Layer. The Convention also committed the signatories to hold workshops and exchange information as the basis for further efforts to achieve a protocol.

Some of the factors that facilitated the Protocol may provide some insight into possible strategies for future efforts to achieve agreements to reduce greenhouse gases (Benedick, 1987). The existence of an international scientific consensus report prepared under WMO auspices, *Atmospheric*

Ozone 1985, helped avoid debate about the underlying seriousness of the problem. The workshop process and informal negotiations that they allowed proved to be very conducive to consensus building. UNEP served a valuable organizing role and provided a valuable objective international forum.

According to the chief U.S. negotiator, U.S. leadership had a major role. "The treaty as eventually signed was based upon the structure and concept advanced by the United States late last year." In addition to governmental efforts, such as a series of diplomatic initiatives, the U.S. role includes industry actions to take responsibility and express support for the proposed emission controls, efforts undertaken by public interest groups to inform the public, and threats of unilateral action and trade sanctions by members of Congress.

International Efforts to Halt Tropical Deforestation

There has also been substantial recent international cooperation on the problem of tropical deforestation. These efforts are of substantial interest because of some of the similarities between the obstacles to solving the tropical deforestation problem and the larger greenhouse problem. In both cases, there is a need for industrialized countries to help developing countries implement policy changes that may be costly and difficult. Mechanisms for achieving international cooperation must be found, substantial amounts of financial assistance must be provided to developing countries, and politically-difficult policy choices must be made.

The Tropical Forestry Action Plan is a promising response to this challenge (WRI, 1985; FAO, WRI, World Bank, UNDP, 1987). The Plan was developed by a consortium of institutions concerned about tropical deforestation, including the U.N. Food and Agriculture Organization (FAO), the U.N. Development Programme (UNDP), the World Bank, the World Resources Institute (WRI), and representatives of more than 60 tropical countries. The task force that drafted the Plan included Brazil's Secretary of the Environment and one of India's former Secretaries of the Environment. The broad and highly-visible sponsorship of the Plan has helped to highlight the important benefits provided by tropical forests and to draw attention to their accelerating loss. Equally important, the Plan offers the broad outlines of a solution, including regional and functional budget proposals. The total budget calls for $8 billion over a five-year period.

The Plan has become a focal point for cooperative efforts by bilateral aid agencies and has influenced World Bank policies (Wolf, 1988; Stowe, 1987).[2] Ultimately, the Plan's success is dependent on the cooperation and support of the affected developing countries, and many of them are preparing national action plans and increasing national support for reforestation (WRI, 1988).

The International Tropical Timber Organization (ITTO) is another important mechanism for north-south cooperation on tropical forest management. The ITTO was created by a March 1985 agreement reached under the auspices of the U.N. Conference on Trade and Development (UNCTAD), primarily as a commodity agreement to facilitate economic use of tropical timber; its purposes include "expansion and diversification of international trade," a "long-term increase in consumption," and greater access to international markets. However, unlike traditional commodity agreements, the ITTO explicitly recognizes the importance to conservation efforts and management policies of the premise of sustainable use. The connection has thus been made between conservation, economic development, and the export of resources to industrialized countries (Wolf, 1988; Forster, 1986).

---

[2] Periodic reports on progress implementing the Action Plan are available from the TFAP Coordinator, FAO Forestry Department, Via delle Terme di Caracalla, 00100 Rome, Italy.

The importance given to promoting cooperation between tropical nations and industrialized consumers of tropical hardwoods is evident in the ITTO organization; the headquarters is in Japan, a very large consumer, and the executive director is from Malaysia, an important producer. Another promising sign is that at the first meeting in April 1987, Japan announced a pledge of $2 million for research on reforestation and sustainable management.

The ITTO also affords a forum for addressing the linkage between industrial country policies and resource exploitation in developing countries. A recent WRI study concludes that "industrial-country trade barriers in the forest products sector have been partially responsible for inappropriate investments and patterns of exploitation in the Third World Forest industries. . . . [N]egotiations between exporting and importing countries should reduce tariff escalation and non-tariff barriers to processed wood imports from the tropical countries, and rationalize incentives to forest industries in the Third World" (Repetto, 1988).

Looking to the future, increased international cooperative efforts will be necessary if tropical deforestation is to be halted and reversed. A possible framework for a program to achieve this goal has recently been outlined by Professor Pedro Sanchez of North Carolina State University (Sanchez, 1988). Dr. Sanchez notes that 12 countries account for three-fourths of the net carbon emissions from clearing primary forests; 10 more account for much of the remainder (Table 9-12). Efforts could be made to engage the leaders of these countries in a dialogue for the purpose of bringing them to specific program agreements targeted to deforestation "hot spots," where technology transfer and government policies would be focused--an approach that is consistent with the Tropical Forest Action Plan's emphasis on national planning.

TABLE 9-12

Countries Responsible for Largest Share of Tropical Deforestation

Country	Net Carbon Emissions in 1980 From Primary Forests (million tons)
Brazil	207
Columbia	85
Indonesia	70
Malaysia	50
Côte d'Ivoire	47
Mexico	33
Thailand	33
Peru	31
Nigeria	29
Ecuador	28
Zaire	26
Philippines	21

Source: Sanchez, 1988.

Ongoing Efforts Toward International Cooperation

Some important first steps to promote international action have already been taken in the last few years and a foundation for international cooperation now exists. Several meetings without formal governmental status established a basis for international scientific cooperation. A conference on the status of the greenhouse problem, organized by the United Nations Environment Programme (UNEP), World Meteorological Organization (WMO), and International Council of Scientific Unions (ICSU), was held in October 1985 in Villach, Austria and was attended by experts from 29 countries, which included representatives from several U.S. agencies. Among their conclusions were recommendations that "scientists and policy-makers . . . begin an active collaboration to explore the effectiveness of alternative policies and adjustments." In response to the recommendations, a small task force was created to advise on needed domestic and international actions and to evaluate the need for efforts to initiate consideration of a global convention.

The government of Canada convened a non-governmental meeting on "The Changing Atmosphere" in June 1988, which was attended by more than 300 experts from 46 countries and several United Nations' organizations. The Conference Statement that resulted from the meeting urges development of an Action Plan for the Protection of the Atmosphere in addition to several specific proposals for government policy, including:

- directing energy R&D budgets to energy options that would greatly reduce CO_2 emissions;
- reducing CO_2 emissions by 20 percent of 1988 levels by the year 2005, half by reducing energy demand and half by changing the sources of energy;
- initiating development of a comprehensive global convention as a framework for protocols on the protection of the atmosphere; and
- establishing a World Atmosphere Fund, financed in part by a levy on fossil-fuel consumption in industrialized countries to help finance the Action Plan.

UNEP and WMO have continued their activities since the 1985 Villach meeting: An Intergovernmental Panel on Climate Change, organized by UNEP and WMO, met in November 1988 with representatives from __ countries. Participants agreed to establish three committees, the first to assess the state of scientific knowledge on the greenhouse issue, chaired by the United Kingdom, the second to assess social and economic effects from global warming, chaired by the Soviet Union, and the third to evaluate potential response strategies, chaired by the United States.

The U.S. also has some important bilateral cooperation with some of the other nations that emit large amounts of greenhouse gases, particularly the USSR and the People's Republic of China. (These three countries account for over 40 percent of the current commitment to global warming.) U.S./Soviet cooperative efforts include studies of future climates, climate studies in the Arctic, measurements of methane and ozone change in the polar regions, and analysis of possible response strategies. The joint communique released after the Reagan-Gorbachev Summit emphasized the high level of interest in cooperation on the greenhouse issue: "The two leaders approved a bilateral initiative to pursue joint studies in global climate and environmental changes through cooperation in areas of mutual concern . . . there will be a detailed study on the climate of the future. The two sides will continue to promote broad international and bilateral cooperation in the increasingly important area of global climate and environmental change."

The U.S. and Soviet Union also have some relevant cooperative activities designed to promote energy conservation. For example, the National Academy of Sciences and the Soviet Academy of Sciences have a cooperative program on energy conservation that includes some comparative evaluation of building codes and other energy conservation programs in addition to exchange of technical information.

The U.S. Government has also initiated cooperative research on climate change with the People's Republic of China, now the world's largest user of coal. Potential areas for cooperative research include exchange of information and development of data on future energy development paths, emissions from rice fields and other sources, and concentrations of trace gases in remote regions.

REFERENCES

Barnes, __., and __. Binswanger. 19_.

Benedick, R. 1987. Report for Montreal: A Landmark Global Treaty to Protect the Ozone Layer. In *Preparing for Climate Change*.

Bernardini, __. 198_.

Bhatia, __. 19_.

Chandler, W. 1986. *The Changing Role of the Market in National Economies*. Worldwatch Paper 72, Washington, D.C.

Chandler, W., H. Geller, and M. Ledbetter. 1988. *Energy Efficiency: A New Agenda*. ACEEE, Washington, D.C.

Dadi, Z. 1988. Energy Price Management and Economic System Reform. Paper presented at the China-U.S. symposium on energy markets and the future of energy demand, Nanjing, China, June 22, 1988.

Daffern, E. 1987. *World Bank Policy in the Promotion of Energy Producing Projects in Developing Countries*. Paper presented in Reading, England, April 7, 1987.

Federal Register. August 12, 1988.

FAO (Food and Agricultural Organization of the United Nations), WRI (World Resources Institute), World Bank, and UNDP (U.N. Development Programme). 1987. *The Tropical Forestry Action Plan*.

FAO . . . (as above). 1987. *The Tropical Forestry Action Plan: Investment Priorities and Policy Reforms for Sustainable Forest Land Use*. Keynote paper prepared for the Bellagio Strategy Meeting on Tropical Forests. July 1-2, 1987.

Flavin, C. 1988. Creating a Sustainable Energy Future. In Brown, et al., eds., *State of the World 1988*. New York, 22-40.

Forster, M. 1986. Two Cheers for the Agreement. *Environmental Policy and Law* 16(5): 142-143.

Geller, H., J. Goldemberg, J. Moreira, R. Hukai, C. Scarpinella, and M. Ysohizawa. 1988. Electricity Conservation in Brazil: Potential and Progress. *Annual Review of Energy* 13:469-483.

Goldemberg, J., T. Johansson, A. Reddy, and R. Williams. 1987. *Energy for Development*. World Resources Institute, Washington, (p. 79)

Goldemberg, J., T. Johansson, A. Reddy, and R. Williams, 1987. *Energy for a Sustainable World*. World Resources Institute, Washington, D.C.

Goldemberg, J., T. Johansson, A. Reddy, and R. Williams, 1988. *Energy for a Sustainable World*. Wiley Eastern, New Delhi.

Gray, J., W. Davis, and J. Harned. 1988. *Energy Supply and Use in Developing Countries*. University Press, New York.

Hill, __. 1987.

Hindu Survey. 1988.

IDEA Inc. 1988. Forestry Project Database, Forestry Support Program.

IIED (International Institute for Environment and Development) and WRI (World Resources Institute). 1987. *World Resources 1987*. Basic Books, Inc., New York, 369pp.

IMF (International Monetary Fund). 1985. In Goldemberg et al., 1987.

Joyce, S., and B. Burwell. 1985. *Community Level Forestry Development: Options and Guidelines for Collaboration in PL 480 Programs*. Washington, D.C., Peace Corps and AID.

Leach, __. 1987.

Leach, __. 1988.

OECD/IEA (Organisation for Economic Co-operation and Development and International Energy Agency). 1987. *Energy Conservation in IEA Countries*. OECD/IEA, Paris.

Miller, A., I. Mintzer, and S. Hoagland. 1985. *Growing Power: Bioenergy for Development and Industry*. World Resources Institute, Washington, D.C.

Munasinghe, M. and R.J. Saunders. 1986. Electric Power Policy in Developing Countries. *Proceedings of the IAEE Conference*. Boston, Massachusetts, Williams 19??.

Repetto, R. 1988. *The Forest for the Trees? Government Policies and the Misuse of Forest Resources*. World Resources Institute, Washington, D.C.

Rich, B. 1985. Multilateral Development Banks, Environmental Policy, and the United States. *Ecology Law Quarterly* 12:681.

Rubinoff, I., 1985. *How to Improve the Conservation of Tropical Forest Ecosystems. Paper presented at the Tropical Forest Conservation Symposium sponsored by the Smithsonian Institution, Friends of the National Zoo, and the World Wildlife Fund-US, December 4-6, 1985, Washington, D.C.*

Sanchez, P. 1988. *Deforestation Reduction Initiative: An Imperative for World Sustainability in the Twenty-First Century*. Paper presented at the Bureau of Science and Technology, U.S. Aid, Washington, D.C., July 22, 1988.

Sathaye, J., A. Chirardi, and L. Schipper. 1987. Energy Demand in Developing Countries: A Sectoral Analysis of Recent Trends. in *Annual Review of Energy 1987* 12:259.

Sathaye, __, et al.? 1988.

Schipper, __. 198_.

Shea, C. 1988. "Shifting to Renewable Energy." In *State of the World 1988*. Worldwatch, New York: W.W. Norton.

Siddiqi, __. 19__.

Stoel, T., A. Miller, and B. Milroy. 1980. *Fluorocarbon Regulation: An International Comparison*. Lexington, Massachusetts.

Stowe, R. 1987. United States Foreign Policy and the Conservation of Natural Resources: The Case of Tropical Deforestation. *Natural Resources Journal* 27 (Winter): 55-101.

U.S. AID (U.S. Agency for International Development). 1987. *Special Report: The Environment*. AID, Washington, D.C.

U.S. AID (U.S. Agency for International Development), 1988a. *Energy and the Environment: An Appraisal of Energy Assistance Strategies for Minimizing Environmental Impacts in Developing Countries*. AID, Washington, D.C.

U.S. AID (U.S. Agency for International Development). 1988b. *Power Shortages in Developing Countries: Magnitude, Impacts, Solution, and the Role of the Private Sector*. U.S. AID, Washington, D.C.

U.S. AID (U.S. Agency for International Development), 1988c. *Progress in Conserving Tropical Forests and Biological Diversity in Developing Countries*. U.S. AID, Washington, D.C.

Williams, R. 1988. *Are Runaway Energy Capital Costs a Constraint on Development?* Paper presented at the International Seminar on the New Era in the World Economy, Sao Paulo, Brazil, August 31 - September 2, 1988.

Williams, R., E. Larson, and M. Ross. 1987. Materials, Affluence, and Industrial Energy Use. *Annual Review of Energy* 12:99-144.

Wolf, E. 1988. Avoiding a Mass Extinction of Species. In Starke, L., ed., *State of the World 1988*. W.W. Norton, New York, 101-117.

World Bank. 1983. *The Energy Transition in Developing Countries*. World Bank, Washington, D.C.

World Bank. 1987. *Annual Report 1987*. Washington, D.C.: World Bank.

World Bank News. January 14, 1988.

WRI (World Resources Institute). 1985. *Tropical Forests: A Call for Action*. WRI, Washington, D.C.

WRI (World Resources Institute). 1988a. Summary of the WRI/EPA Workshop on Greenhouse Gas Emissions and Sustainable Development. Washington, D.C.

WRI (World Resources Institute). 1988b. *International Conservation Financing Project: Maintaining Biodiversity and Critical Ecosystems in Support of Sustainable Development, Preliminary Paper on Financing Mechanisms*. World Resources Institute, Washington, D.C.

WRI (World Resources Institute). 1987. *World Resources 1987*. Basic Books, Inc., New York, 369 pp.

WRI (World Resources Institute) and IIED (International Institute for Environment and Development), 1988. World Resources 1988-89. New York: Basic Books, Inc.

WRI (World Resources Institute), World Bank, and UNDP (United Nations Development Programme). 1985. *Tropical Forests: A Call for Action*. Washington, D.C.: World Resources Institute.

United Nations. 1986.

U.S. Treasury Department. 1988. *Progress Report on Implementation of Environmental Reform in Multilateral Development Banks*. Treasury Department, Washington, D.C.

*U.S. GOVERNMENT PRINTING OFFICE:1989-620-710:00960